THREATS
TO SOURCES OF DRINKING WATER
AND
AQUATIC ECOSYSTEM HEALTH IN CANADA

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Foreword

Scientists and managers at the National Water Research Institute identified a list of 13 water quality related threats to sources of drinking water and aquatic ecosystem health. Four of the threats: nutrients, acidification, endocrine disrupting substances (EDS) and genetically modified organisms (GMOs) were recently addressed with broad participation through workshops. The remaining nine threats were pathogens; algal toxins; pesticides; long-range atmospherically transported pollutants; municipal wastewater effluents; industrial wastewater discharges; urban runoff; solid waste management practices; and water quantity changes affecting water quality due to climate change, diversions and extreme events. To address these remaining nine threats, a Workshop was organized and facilitated by the National Water Research Institute. There were 45 participants from Environment Canada and a number of other organizations. Teams were identified for each threat and charged with preparing short draft reports on the Current Status, Trends, and Knowledge and Program Needs of each threat in Canada. Some of the threats are groupings of similar contaminants, for example pesticides, while others are sources of a mixture of contaminants, for example municipal wastewater effluents. Because of this, there is some overlap between several of the identified threats, and there was considerable interaction between the teams. Subsequent to the workshop, two additional threats were identified, teams assembled and draft reports produced. These threats were aquatic ecosystem impacts of agricultural and forestry practices and naturaly occurring contaminants. The Executive Summary consists of abbreviated statements on each Threat. The intent is to give a flavour of the Current Status, Trends, Knowledge and Program Needs for each threat. This is followed by the 15 reports themselves.

Executive Summary

1. Waterborne Pathogens

Waterborne pathogens can pose a problem to drinking water supplies, recreational waters, and source waters for agriculture, and aquaculture. Sources of pathogens include municipal wastewater effluents, urban runoff, agricultural wastes and wildlife. A drinking water incident in Milwaukee in 1993 killed 54 people and made 400,000 sick. From 1974 to 1996 there have been over 200 outbreaks of infectious diseases in Canada associated with drinking water. Pathogen contamination of irrigation water or shellfish beds can also pose risks to human food supplies. In addition, declines in amphibian populations may be related to fungal or viral pathogens. There is a need to study the consequences of environmental releases of microbial pathogens because there is inadequate knowledge of the sources, occurrence, concentrations, survival and transport of specific microorganisms in the environment. Enhanced funding is needed to validate newer molecular detection tools, understand the ecology of pathogens in aquatic ecosystems, better predict disease outbreaks, and improve emergency responses. A preventive approach to pathogen pollution should be taken by Canada in the form of a source water protection program for all major freshwater bodies.

2. Algal Toxins and Taste and Odour

Algal toxins in stock watering sources have killed animals and may affect their health. In Brazil, 50 people died due to algal toxins in water used for hemodialysis in 1996. Toxins can attack the liver, the nervous system or irritate skin, yet very few of these toxins have been isolated and characterized. Reliable prediction of blue-green algal blooms is rare but is thought to be related to nutrient loads. Taste and odour problems in potable water are increasing worldwide and are produced by microorganisms such as bacteria and fungi. However, the toxicological properties of taste and odour compounds are scarcely known. Taste and odour problems occur in British Columbia, the Prairie provinces, Ontario and Quebec, and their frequency is increasing. Because toxins in raw and finished water are poorly studied, there is a need to know seasonal trends in their concentration and production. The triggers for toxin-producing algal blooms need to be better understood. There is likewise a lack of knowledge of the sources and triggers of taste and odour compounds. Also, little is known of the chemistry and biological fate of taste and odour compounds, and potential health effects from their consumption, dermal contact and inhalation should be checked. Treatment technologies for drinking water plants should be optimized to deal with algal toxins and taste and odour causing compounds.

3. Pesticides

Synthetic chlorinated pesticides were introduced in the 1940s and 1950s but serious environmental problems only began to be noticed in the 1960s and 1970s. There are 550 pesticide active ingredients currently registered in Canada under PCPA, and PMRA is committed to re-evaluating 400 older pesticides (registered before 1995). Groundwater and surface water contamination by pesticides will likely intensify. Thus, a better understanding is needed of the sources, fate and effects of pesticides and their degradation products. Unfortunately, there is a lack of a coordinated, interjurisdictional system for monitoring pesticides in Canada. With climate change, changing agricultural practices may change pesticide use patterns. Also, the introduction of new pests to Canada may require increased targeted pesticide use. In addition, the toxicological significance of constant exposure to low levels of pesticides is unknown and research is also needed on the chemical analysis of ultra-low levels of pesticides. With recent advances in GMOs, there is a need to determine hazards of genetically expressed pesticides in crops. Research is needed on risk assessment methodologies and into the effectiveness of risk mitigation and risk management options.

4. Persistent Organic Pollutants and Mercury

Persistent organic pollutants (POPs) comprise a group of chemicals that degrade slowly in the environment, bioaccumulate and have toxic properties. Substantial historical reservoirs exist for many POPs in the Canadian environment. Mercury (Hg) is a natural element but behaves like a semi-volatile organic compound and is transported through the atmosphere almost entirely as gaseous mercury. Great Lakes and Arctic communities with high consumption of fish, even with low levels of POPs and Hg, can exceed tolerable daily human intakes. In biota, there has been a twofold increase from 1975 to 1995 in Hg in thick-billed murre eggs in the Arctic. New compounds such as flame retardants are used in the manufacture of plastics, paints, textiles and electrical devices. There has been a 65-fold increase between 1981 and 1999 of flame retardants in Lake Ontario gull eggs. Because several older pesticides can be detected in sites far removed from areas of former use, long-range atmospheric transport is indicated. Research is needed on the toxicology of individual compounds of POPs such as toxaphene and basic physical property information is needed on new POPs, especially at temperatures relevant to Canada. The capacity to link chemical measurements of POPs to biological effects needs to be strengthened. Models to predict the trends in environmental levels of old and new POPs need to be refined. There is still uncertainty about anthropogenic versus natural sources of Hg and detailed investigations of the Hg biogeochemical cycle are needed. Development of capacity to precisely measure stable isotopes of Hg is needed to help resolve the natural versus anthropogenic source questions.

5. Endocrine Disrupting Substances

Endocrine Disrupting Substances (EDS) can exert an array of effects on growth, development and reproduction in biota at extremely low concentrations and these effects can be expressed in future generations. EDS include drugs, pesticides, industrial chemicals, metals and natural compounds, and are found in municipal, agricultural, textile, pulp and paper, and mining effluents. The effects of EDS include deformities and embryo mortality in birds and fish and they depress thyroid and immune functions in fish-eating birds. Cognitive and neurobehavioural effects in infants can be related to prenatal exposure to EDS. EDS will thus continue to be a high-profile international issue. Priority research should go to sites, sectors and populations having the highest potential for effects and should focus on functional endpoints of growth, reproduction and development during critical life stages. Environmental and human health monitoring programs should be enhanced. Laboratory testing needs to be related to ecological significance in the environment and work with international agencies is required to validate currently proposed tests for EDS effects. Better knowledge is needed of low-dose effects and thresholds, and a framework for risk assessment of EDS in mixtures and effluents should be developed. A weight-of-evidence approach should be used to make appropriate decisions.

6. Nutrients—Nitrogen and Phosphorus

Nitrogen (N) or phosphorus (P) limited productivity in aquatic ecosystems prior to human settlement and development of agriculture. Today, the amount of N and P available for plant uptake has increased dramatically and available N has doubled since the 1940s and human sources of P greatly overshadow natural sources. These increases in N and P can accelerate eutrophication of surface waters and wetlands, and increase the frequency of toxic algal blooms leading to risks to humans. The nitrate drinking water guideline is exceeded in groundwater in many parts of Canada. Nutrient losses from intensive livestock operations are likely to rise and aquaculture is a growing source of nutrients to surface waters. Knowledge is needed on how nutrients induce algal blooms and toxin production and the role of nutrients in causing taste and odour problems. Effects of forestry and agricultural land use on nutrient losses need to be assessed. The relationship between nutrients and aquatic plant biomass in streams is not understood. Nutrient guidelines are needed to protect aquatic life in different water bodies, with nutrient management plans and codes of practice developed for sectors such as agriculture or aquaculture, and watershed management plans for specific basins.

7. Aquatic Acidification

For many years, Canadian research has been in the vanguard of defining the aquatic effects of acid rain. Scientific consensus justified SO_2 and NO_x emission controls in Canada and internationally, and both Canada and the U.S.A. have significantly reduced SO_2 but not NO_x emissions. Reproduction and death of fish species are linked to low pH with resultant effects on aquatic birds due to changes in quality and quantity of food. Given present SO_4^{2-} deposition, critical loads will still be exceeded for most of Canada's monitored lakes, while there have been few cases of natural recovery of fish communities. In southeastern Canada, some 76,000 lakes will remain chemically damaged unless additional SO_4^{2-} emission reductions are continued. New surveys must be conducted if assessment of changes is to be made. Meanwhile, the nitrogen status of lakes and catchment basins remains unknown. The status of the soil base cation pool and its replenishment rate, and the size and reactivity of the stored sulphur pool are also unknowns. Models should be modified to include nitrogen-based acidification. In situ assessment of the toxicity of acidification episodes needs to be conducted. The interactions of acidification recovery with future climate change also need to be assessed.

8. Ecosystem Effects of Genetically Modified Organisms

The use of genetically modified organisms (GMOs), specifically genetically modified (GM) crops, began in the 1990s in Canada, has grown significantly, and is projected to continue to do so. The only GMOs registered in Canada to date are microbes for sediment remediation and GM crops. So far, there have been no attempts to register GM fish or GM trees. Nevertheless, there is already a need to know the long-term cumulative impacts on biodiversity resulting from the dispersal of GMOs in the environment. We need to know the uncertainty involved in current short-term, small-scale risk assessments carried out by regulators and develop adequate predictive capacity in extrapolating from the lab or small plot scale to much larger scales. The potential impacts of engineered insecticidal residues on soil and stream microorganisms and invertebrates is also unknown. The most sensitive diagnostic molecular biological tools should be used to answer these questions.

9. Municipal Wastewater Effluents

These effluents (MWWE) are a complex mixture of human waste, suspended solids, debris and a variety of chemicals derived from residential, commercial and industrial sources. They comprise the largest source of effluent discharge to Canadian waters, and population growth and urbanization will continue to increase them. MWWE are a source of endocrine disrupting substances, pharmaceutical, and personal care products, among other contaminants. There is a need to better understand the sources, fate and distribution of priority and toxic substances in municipal treatment systems. Sludges generated at municipal wastewater treatment plants are applied to lands and their impact on surface and ground water needs to be assessed. Waste treatment and disposal quality criteria, objectives and standards should be based on the assimilative capacity of the receiving waters. Municipal wastewater planning should be integrated as part of overall watershed planning.

10. Industrial Point Source Discharges

Pulp and Paper

In the year 2000, there were some 125 pulp and paper mills across Canada and a typical mill generates some 90 to 130 million litres of effluent per day. The effects of these effluents consist of chronic toxicity to aquatic organisms and eutrophication. Although the volume of pulp mill effluents is expected to decrease, concentrations may increase. Colour and taste and odour have been detected 900 km downstream of pulp mills. Of the mills in Canada, 80% report effects of effluents on fish.

Mining

There are 900 present or former mining sites for base metals, gold, potash, coal and iron ore across Canada and most sites are adjacent to freshwater systems in remote areas. At active mines, concerns include chronic effects of metals, bioaccumulation, sediment contamination, and endocrine disruption and closed or abandoned mines also contribute contaminants to local water systems. Many new mines are anticipated in remote, sensitive environments such as the Arctic.

Petrochemical

Petrochemicals are extracted by oil and gas drilling and oil sands mining. Although there are few direct effluent discharges to water due to extraction, with the exception of the oil sands, petrochemical refineries are located on water bodies that can provide cooling water. Many petrochemical by-products are toxic, hydrophobic and persistent, and adjacent water bodies often contain highly contaminated sediments. Long-term implications for aquatic biota in waters receiving Oil Sands Process Waters are unknown while the oil sands are expected to triple production over the next 20 years.

The implications of pulp mill discharges to drinking water quality are still largely unknown because the identity of causative agents such as EDS remain unknown. There is a need to distinguish natural effects from industry-related effects and to include drinking water endpoints in ecological assessments of water quality for all industrial discharges. An ongoing monitoring program, similar to the EEM for pulp and paper mills, is also needed for the mining and petrochemical industries. There is a need to develop cumulative effects assessments and emphasize integrated watershed management. Ecologically based assessment criteria should be incorporated into environmental management strategies. Development of novel technologies to reduce impacts of effluents on water quality should be encouraged.

11. Urban Runoff

Urban runoff transported by sewers, drainage channels and streams is ultimately discharged to receiving waters. Urban runoff is a mixture of storm water, raw sewage and scoured sewage. Impacts on human health are through contamination of source drinking water, fish and shellfish, recreational water, and breeding grounds for disease vectors such as encephalitis. Current practices of urban development are not sustainable with respect to receiving water quality. Infectious diseases may inhabit urban wetlands used to control runoff. There is a need to better understand the sources, pathways and fate of contaminants and microbial pollutants in the complete urban environment. There is a need to update data on the composition of storm water runoff. Total urban water cycle management is required and protocols are needed for the protection of urban water supplies from all hazards. National standards should be developed for the design and operation of urban water systems.

12. Landfills and Waste Disposal

Canada ranks among the highest producers of solid waste in the industrial world. These wastes are produced from domestic, commercial, industrial and agricultural activities. Drinking water sources in groundwater-dependent communities like Elmira, Ontario; Abbotsford, B.C.; and Ville Mercier, Quebec, have been contaminated by poor waste disposal and groundwater contamination can damage drinking water supplies for decades to hundreds of years. Nutrients, metals, and volatile organics are often detected in aquifers several kilometres from landfill sources. Effects of mining wastes have been projected to last decades to centuries to millenia. Contaminants in livestock waste include nitrate, ammonia, coliform bacteria, phosphorus, endocrine disrupters and pharmaceuticals. Biosolids from sewage treatment plants are disposed of in landfills and spread on land and contain the same contaminants as animal wastes. As Canada's urban population grows, so does the amount of municipal waste, and the number of septic systems will continue to increase dramatically. Also, the importation of hazardous wastes from other countries has increased. Meanwhile, there are gaps in knowledge of the mobility of new chemicals such as POPs and EDS in landfills; transport of contaminants across the groundwater-surface water interface; and long-term release of nutrients and metals from biosolids. There needs to be effective implementation of aquifer remediation and treatment systems. New regulations rather than guidelines for waste disposal are needed along with harmonization of regulations and guidelines among all levels of government. Realistic bonding should be in place to deal with long-term problems and abandoned sites.

13. Agricultural and Forestry Land Use Impacts

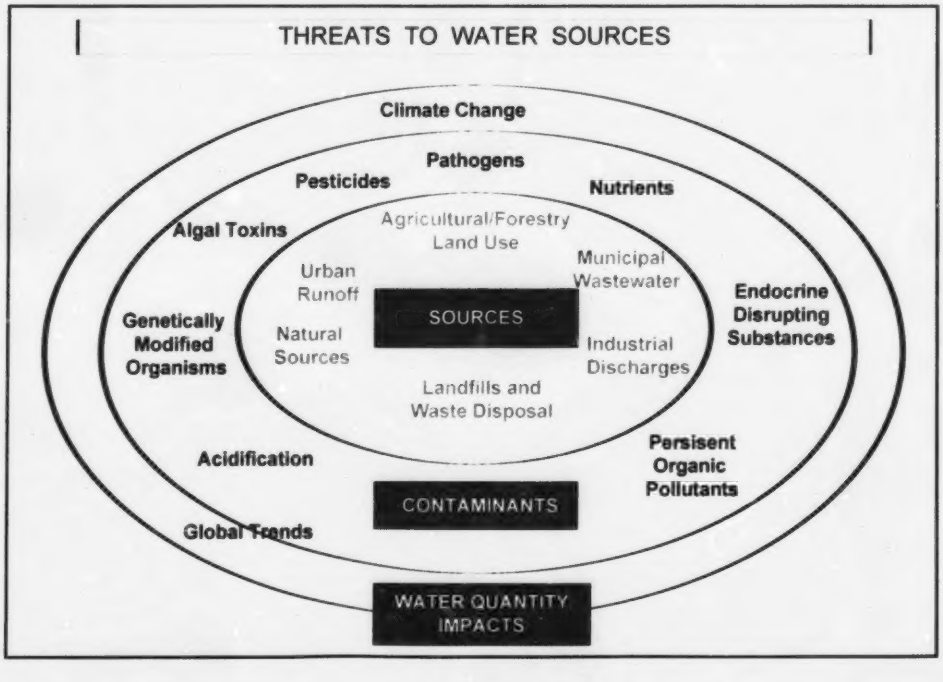
In Canada, approximately 12% of the total land base is currently managed for timber harvest, another 7% is used for farming and an additional 1% is in urban/industrial development. Timber harvest can increase water yield, suspended solids and temperature in streams; disrupt the cycle of nutrients between the soil and trees; and increase concentrations of dissolved nitrogen, organic carbon, base cations and phosphorus in streams and lakes. Although timber harvest is expected to continue in order to meet market demand, hydrologic, chemical and biological impacts on streams and lakes from forest management practices have been defined for relatively few sites. Intensification of agricultural production has increased the risk of water contamination unless substances such as mineral fertilizers, pesticides and manure are adequately managed. Pesticides are frequently detected in surface waters draining cropland. There is a need to study the environmental and human health consequences of nutrient, pathogen, pharmaceuticals and endocrine disrupting substances added to surface and ground waters from agricultural practices. There is inadequate knowledge of biogeochemical and hydrological cycles to predict the effects of changes in agricultural and forestry land management practices on water resources. Enhanced funding is needed to validate newer molecular detection tools, understand the ecology of pathogens in aquatic ecosystems, better predict disease outbreaks, and improve emergency responses. Scientifically credible practices, standards, and codes for agriculture and forestry operations, together with appropriate enforcement mechanisms, should be established to ensure protection of ground and surface waters and aquatic biota.

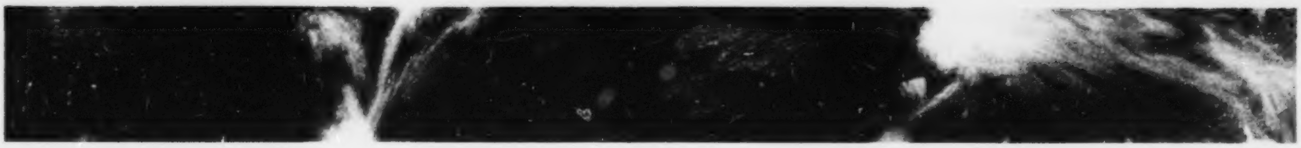
14. Natural Sources of Trace Element Contaminants

Natural geologic sources of trace element contaminants exist in many regions of Canada. These sources threaten groundwater and surface waters. For example, on the Prairies, arsenic in groundwater is locally above safe limits; in the Moncton area, fluoride levels are high; and naturally high levels of radioactivity and radon are associated with granitic terranes. Mapping of the geologic sources of contaminants shows clearly where some anomalies exist, but is far from complete. There is thus a need for further mapping of the geochemical landscape, research on speciation and bioavailability of trace elements, and a horizontal approach among agencies to determine the severity of the threat.

15. Impacts of Dams/Diversions and Climate Change

Impacts of water quantity changes on water quality are based largely on studies of the effects of Canada's 600 dams and 60 large interbasin diversions. Changes to water quantity modify various water-quality parameters within the reservoir and downstream and flow diversions also produce major changes in water quality. Variations in climate can produce major changes in both water quantity and quality. For example, historical sources show earlier ice breakup and later freezing dates on lakes and rivers in recent years. The Canadian climate will be increasingly warmer and wetter. In the Great Lakes basin there will be reduction in annual streamflow and lake levels, but an increased frequency of flood events. In some areas, the current sewage treatment facilities are unlikely to accommodate the increased volume of stormwater and sewage runoff. The Prairies will experience the most pronounced drying of any region in Canada. In such semi-arid regions, first-order streams may become ephemeral, many ponds and wetlands will completely disappear and lakes will become disconnected. There is a need to improve climate forecast scenarios, and down-scale global models for use in hydrological and ecological models. Better understanding is required of the interactions between hydrological processes and biogeochemical responses; effects of changes in water quantity/quality on ecosystem structure and function; and interaction between changing hydrologic regimes and aquatic habitat quality. Knowledge is needed about water balances in altered landscapes and better methods are needed to predict how changes in the climate system affect the hydrologic cycle. Instrumented basins should be established or enhanced in representative regions and a Canadian Hydro-Ecology Research Network established.





1. WATERBORNE PATHOGENS

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Current Status

The emergence and spread of infectious disease in plant, animal and human populations is a problem in Canada and around the world. Water is a common element in the ecology of many pathogens affecting these populations. Waterborne pathogens can pose threats to drinking water supplies, recreational waters, source waters for agriculture and aquaculture, as well as to aquatic ecosystems and biodiversity.

The World Heath Organization has stated that infectious diseases are the world's single largest source of human mortality (WHO 1996). Many of these infectious diseases are waterborne and have tremendous adverse impacts in developing countries. While developed countries have been more successful in controlling waterborne pathogens, water quality problems are still prevalent in Canada and the United States. Based on U.S.A. estimates (ASM 1999a), it is possible that about 90,000 cases of illness and 90 deaths occur annually in Canada as a result of acute waterborne infections. Waterborne pathogens can pose significant human health threats as the drinking water outbreak in Walkerton, Ontario, demonstrated last year, where seven people died and 2500 became ill. A drinking water incident in Milwaukee, Wisconsin, in 1993 resulted in 54 deaths and over 400,000 cases of illness (Hoxie et al. 1997).

Waterborne disease outbreaks in Canada have been monitored by Health Canada since 1974. Between 1974 and 1996, the last year for which data are available, over 200 outbreaks of infectious disease associated with drinking water were reported (Todd and Chatman 1974–1996). There were greater than 8000 confirmed cases linked to these outbreaks. However, depending upon the severity of the symptoms, the actual number of cases can be 10 to 1000 times greater than the number of reported cases. Public attention has recently focused on a variety of drinking water threats from bacteria (*E. coli* O157:H7 in Walkerton, Ont., in 2000), to protozoa (*Toxoplasma gondii* in Victoria, B.C., in 1995) and viruses (Hepatitis A in Ile d'Orleans, Que., in 1995).

Bacteria (primarily *Salmonella*, *Shigella* and *Campylobacter*) were responsible for 78 drinking water outbreaks in Canada between 1974 and 1996. Protozoa and unidentified pathogens were responsible for 59 and 43 outbreaks, respectively. Enteric viruses, primarily Norwalk and Hepatitis A, were responsible for 23 outbreaks. The number of outbreaks caused by protozoa is particularly interesting. In 1990, the cumulative total was only 20, but outbreaks caused by protozoa have tripled since then. Most of these outbreaks were caused by *Giardia*, but in 1993 the first reported outbreak caused by *Cryptosporidium* occurred in Canada. Since then, outbreaks of giardiasis and cryptosporidiosis have occurred in all regions of the country. In 1995, the first outbreak of toxoplasmosis (*Toxoplasma gondii*) linked to a municipal drinking water supply occurred in British Columbia. The large number of outbreaks caused by unknown agents is also of interest. It is probable that many of these were caused by enteric waterborne viruses.

Waterborne pathogens also pose threats to ambient recreational waters resulting in illnesses and economic impacts on local communities. From 1992 to 1995 there were 2839 beach closings reported for 169 public beaches on lakes Ontario, Erie, Huron and Superior (Health Canada 1998). Pathogens such as *Cryptosporidium* and *Giardia* are known to occur across Canada in aquatic ecosystems that serve as sources of recreation and drinking water. As an example, a study of waterborne pathogens has been underway in southern Alberta since mid-1999 (J. Byrne, personal communication). Health Canada and University of Lethbridge research scientists have monitored *Salmonella*, *E. coli* 0157:H7 and coliform/fecal coliform (C/FC) populations in the Oldman River basin. This area includes an extensive network of irrigation canals associated with intensive livestock production. In 1999 and 2000, a number of these pathogens were identified, with pathogen populations peaking in mid to late summer of both years. In late July 2000, almost half of the monitoring sites tested positive for one or more pathogens and researchers found *E. coli* 0157:H7 in Park Lake, Park Lake Provincial Park, one of the most popular recreation locations in southern Alberta. FC populations in the Oldman basin typically exceeded the Guidelines for Canadian Recreational Water Quality (GCRWQ) in most samples, and in many cases, FC counts exceeded GCRWQ by a factor of five or more.

Pathogen contamination of aquatic ecosystems is known to occur from a range of sources including municipal wastewater effluents, agricultural wastes, and wildlife. This contamination can pose threats to water sources required for agriculture and aquaculture.

For example, pathogen contamination of irrigation waters or shellfish areas can pose risks to human food supplies. Such pathogen threats can lead to significant health care and economic impacts as well as significant trade implications and intrusive disease controls. Aquaculture exists in intimate contact with aquatic ecosystems. The presence of pathogens in source waters can severely limit success of food fish production for domestic consumption and export (Hedrick 1998).

Another critical aspect of waterborne disease is the threat that pathogens can pose to aquatic ecosystems and biodiversity. Much like the concern about emerging human pathogens, there is growing concern about non-human pathogens and their impacts on wildlife and biodiversity in Canada and around the world (CCWHC 1999; Daszak et al. 2000). For example, outbreaks of botulism caused by *Clostridium botulinum* have caused substantial waterfowl mortalities at locations across Canada. In addition, newly emerging fungal and viral pathogens have contributed to significant declines in amphibian populations around the world from frogs in South America to tiger salamanders in Saskatchewan (Carey 2000).

The current status of many pathogen threats to drinking water and aquatic ecosystems remains uncertain although they are likely underestimated. These threats are accompanied by growing concerns about pathogens as causative factors in chronic diseases such as ulcers, cancer and heart disease where infectious agents were not previously suspected of being involved (ASM 1999b). Additional surveillance and scientific research is required to better understand the nature of these pathogen threats.

Trends

The emergence and spread of waterborne pathogens is likely to be a growing problem in Canada and around the world. Increasing human population densities, along with rapidly expanding and increasingly intensive livestock/poultry production, pose significant animal and human waste management challenges. The possible threats from "pathogen pollution" will need careful surveillance since it can be anticipated there will be increasing releases of plant, animal and human pathogens into aquatic ecosystems in the future from a wide variety of sources including: municipal wastewaters, septic tanks, land application of sewage sludges, stormwater overflows, slaughter houses and rendering plants, livestock and poultry wastes, landfill sites, and biology-based research and manufacturing facilities. Surveillance efforts will also need to consider the fate of virulence and antibiotic resistance genes from microorganisms released into aquatic ecosystems. The spread of antibiotic resistance through gene transfer events is leading to the emergence of pathogens that are increasingly more difficult and expensive to treat.

Expanded human and agriculture densities can also compress wildlife populations, and increase the risk of amplification and dissemination of pathogens from wildlife into drinking water supplies and water-dependent food supplies. It is also possible there could be increasingly novel pathogen sources from biomedical wastes, or even use of biological weapons, that could lead to contamination of drinking water sources and aquatic ecosystems.

Together, these sources of pathogens will place greater demands on an inadequate and aging wastewater treatment infrastructure in Canada. A strategy will be required to manage the risks to humans, agriculture, aquaculture and aquatic ecosystems from the increasing quantities of potentially infectious wastes that will require storage, handling, transportation, treatment and disposal.

Globalization of travel and trade flows will also place increasing stress on our capacity to assess and control the threat of potentially infectious materials or organisms that may be imported into Canada and enter aquatic ecosystems. Pathogens can be transported across borders in ways such as contaminants in food, ship ballast waters and travelers. The introduction of alien species into aquatic ecosystems could also lead to spread of associated non-native pathogens. Additional pathogen threats to water quality could be posed by water diversions, changing agricultural practices and water use patterns, and global climate change. Climate factors and weather conditions can affect the prevalence and transmission of infectious diseases through effects on vectors like mosquitoes, as well as pathogen reservoirs and hosts.

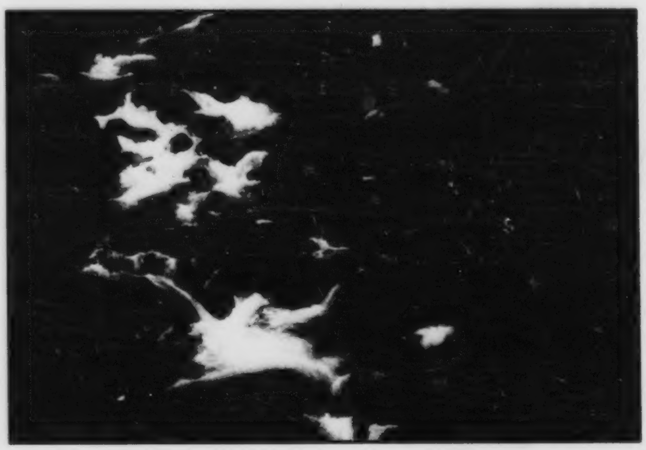
Knowledge and Program Needs

While there has been considerable research to investigate the threats to water quality posed by environmental releases of toxic chemicals, comparatively little effort has been directed at studying the potential consequences of environmental releases of harmful microbial pathogens. The unique nature of microorganisms to replicate rapidly, evolve, transfer genes, and disperse in unusual ways, requires new knowledge and new approaches to understand, assess and control the potential environmental and human health threats of waterborne pathogens. The American Society for Microbiology (ASM) recently drew attention to waterborne pathogens by indicating that control of water pollution in the United States over the past two decades has focused on chemical risks, overshadowing the significant risks associated with microbial pollutants (ASM 1999a). The ASM considers microbial pollution of water in the United States to be a growing crisis in environmental and public health that is not being properly addressed through scientific research and risk assessment. It was indicated that waterborne pathogens pose increasing threats due to changing patterns of water use, increasing water pollution, aging wastewater treatment systems, out-moded risk assessment protocols, and an inadequate knowledge of the sources, occurrence, concentrations, survival and transport of specific microorganisms in the environment.

At present there are only limited surveillance data and knowledge of waterborne pathogens in Canada. Enhanced surveillance and research will be required to understand and control the sources of pathogens entering aquatic ecosystems as well as the epidemiological factors associated with infectious disease outbreaks. For example, new knowledge is needed about the ecology of pathogens in aquatic ecosystems, including their survival, transmission, reservoirs, host ranges and adaptive responses to environmental conditions. This knowledge requirement is particularly acute for non-human pathogens and the threats these pathogens may pose to aquatic ecosystems and biodiversity. Much of the concern and attention about infectious diseases has arisen from a human health and agricultural perspective. At present, there is a significant gap in scientific understanding of the infectious disease issue from a broader ecosystem perspective.

The identification and control of threats posed by waterborne pathogens will also require effective pathogen detection techniques. The value and limitations of traditional pathogen indicators like coliform counts must be evaluated since such indicators are unable to accurately assess the presence of certain protozoan and viral pathogens (OECD 1999). Related to this will be the need to develop, evaluate and validate newer molecular tools for pathogen detection such as PCR techniques and DNA microarrays. Rapid advances in fields such as genomics offer the potential to develop improved pathogen detection tools. The responsibility of governments to carefully monitor advances in pathogen detection technology, and apply these technologies in a timely manner to prevent infectious disease outbreaks, was an integral aspect of the Krever Commission's review of the "public health disaster" related to pathogen contamination of the Canadian blood supply.

- Water management programs in Canada need to take a preventative approach to pathogen pollution and emphasize the importance of source water protection and defining sources of water contamination. Canada should have a source water protection program for all major rivers.
- Canada needs to develop a National Monitoring Program for: i) collection and analysis of baseline data on waterborne pathogens; and ii) identification of hot spot areas that require targeted research and monitoring.
- Wastewater management and water supply systems in Canada need to be re-examined to consider the need for enhanced regulations and guidance for preventing pathogen contamination of aquatic ecosystems.
- Strategic support is needed to enhance funding for waterborne pathogen research in Canada to: i) assess the value of current pathogen indicators; ii) investigate and validate newer molecular detection tools; iii) better understand the ecology of pathogens in aquatic ecosystems; iv) better understand environmental risk factors for predicting disease outbreaks; and v) evaluate current emergency response capacity for pathogens.
- Canada needs to establish a network for research on pathogens in aquatic ecosystems.
- All levels of government need to ensure pathogen pollution prevention concerns are integrated into other water management programs.



Freshwater bodies require protection from pathogens that pose threats to drinking water supplies, recreational waters, agricultural and aquacultural source waters, and to aquatic ecosystems in general.

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2. ALGAL TOXINS AND TASTE AND ODOUR

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Current Status

Algal Toxins

Toxins are produced by blue-green algae (cyanobacteria) and other types of algae in quantities sufficient to cause death of animals and pose a risk to Canadians' health (Chorus and Bartram 1999). Cyanobacteria form heavy growths in ponds, lakes, reservoirs and slow-moving rivers throughout the world. Water blooms are composed of large numbers of cells or filaments, often in colonies. These cells can house toxins called *cyanotoxins*. When the waterbloom mass rises to the surface of the water, it is referred to as a *surface scum* or a *surface water bloom*. Although we do not know the extent to which cyanobacterial blooms occur across Canada, we do know they mostly appear in the hot summer months and are quite prevalent in the Prairie provinces as well as other water bodies across Canada. *Cyanotoxins* are the naturally produced poisons stored in the cells of certain species of cyanobacteria. These toxins fall into various categories. Some are known to attack the liver (hepatotoxins) or the nervous system (neurotoxins); others simply irritate the skin (dermotoxins). These toxins are usually released into water when the cells rupture or die. Most cyanotoxins have been isolated and characterized. Detection methods, including rapid screening, are being developed to help us learn more about them, especially to find out which toxins are a problem in Canada and what conditions encourage their production.

Hepatic Microcystins—the Cyclic Peptides

Sixty-five microcystin toxins have been identified. Toxin problems are associated with blooms of mainly cyanobacteria (blue-green algae) during warm weather. Although high nutrient conditions (eutrophication) are not necessary for blue-greens, the resultant turbid water quality favour blue-greens that can control their buoyancy in order to receive adequate illumination. Monitoring of blue-greens and their toxins is difficult because the buoyant algae can be concentrated by wind by a factor of 1000 or more and even form scums at the downwind end of water bodies. Not all blooms of blue-green algae are toxic even for species known to be toxin producers (Chorus and Bartram 1999). Reliable prediction of blue-green algal blooms is rare but the severity of blooms is partially related to nutrient loads. Predictability of toxin production is difficult or impossible but suspect species are known. Unfortunately, there are few biologists trained in phycology who would be able to identify the algae. Human threats from microcystin toxins have been identified in drinking water (Winnipeg, Regina, central Alberta), recreational water, and irrigation/stock watering sources. Particularly difficult problems exist in ponds and dugouts where no other sources exist. The occurrence of toxins is not restricted to highly eutrophic water or prairie systems; this is shown by the appearance of cyanotoxins in Lake Erie (Brittain et al. 2000). Blue-green algal toxins may be linked to bird deaths due to avian botulism.

Although humans are rarely killed by algal toxins, deaths have occurred in extreme exposures. In 1996, 101 patients were made ill and 50 died due to algal toxins in water used for hemodialysis at one treatment centre in Brazil (Jochimsen et al. 1998). The dose of toxin was delivered through exposure to about 150 litres of contaminated water used in the dialysis treatment. Kidney dialysis centres and home dialysis may be at risk from potentially contaminated water.

The blue-green algal toxin Microcystin-LR is currently used as an indicator for the presence of other toxins. No universal standards for microcystin toxins are available. There is potential for Canadian development of an industry to supply the standards. A field analytical kit is nearing completion at the University of Alberta. There is potential for commercialization of the field kit based on existing strengths, but support is required to complete validation of the procedure. Cost-effective laboratory analytical methods for routine monitoring of toxins are being established at Health Canada. The majority of microcystin toxins are irreversibly bound to tissues in affected animals. Thus, the overall exposure and the toxicity of bound forms is unknown.

Guidelines have been developed to help limit exposure. The proposed toxin guideline for consumption in Canada is 1.5 μg/L (WHO is 1.0, Australia 1.3, U.S.A. 1.0 μg/L). The proposed guideline does not cover potential for cancer risk from microcystin toxins which are likely to be tumour promoters. Human exposure threats from microcystins in the Prairie provinces is being studied by Health Canada in conjunction with the University of Alberta. Much of the Canadian foundation of expertise in algal toxins is centred or originated at the University of Alberta. Canadian expertise and experience is on par with the U.S.A., Australia, U.K. and Japan.

Taste and Odour

The presence of tastes and odours in potable water supplies has been increasing worldwide in both intensity and frequency in recent years. Taste and odour problems have been reported widely in Canadian waters including B.C.; Edmonton; Calgary; Lethbridge; Prairie lakes, ponds and dugouts; Regina; Winnipeg; Muskoka Lakes and Quebec City. In particular, taste and odour problems have increased in the lower Great Lakes and the St. Lawrence River (SLR). The occurrence in Great Lakes drinking water produces an aesthetic problem for millions of consumers, but in addition, invariably raises uncertainty about the safety of the drinking water frequently expressed by the public as "Is the water safe to drink and bathe in?"

Taste and odour compounds can be man-made (industrial, municipal, etc.) or biogenic. This section will focus on biological compounds. Taste and odour compounds are produced by microscopic organisms such as algae, bacteria, fungi and protozoa. They represent a wide variety of odourous compounds that can be detected by our olfactory senses in very low concentrations at the parts per trillion level (ng/L). The most common compounds produce earthy, musty tastes and odours. Two compounds, geosmin and 2-methylisoborneol (MIB), have been widely reported. In some cases, production of these compounds occurs in situations where high nutrient conditions favour blooms of known algae producers. However, the recent occurrences in the Great Lakes come at a time where nutrient levels have reached their lowest levels in decades. In these cases, the sources of these compounds are unknown (algae or bacteria). Nutrient-poor lakes and reservoirs can have different compounds (fishy odour) produced by chrysophyte algae (Watson et al. 1999).

The taste and odour problems mainly occur in late summer—some are in winter under ice, but the intensity can vary from severe to innocuous year to year. Predictability of the problems is low. Little is known about the environmental conditions that trigger their production. Taste and odour compounds may come from species living in the water, on surfaces, in the bottom sediments or may be produced onshore and washed into the waters during runoff events. Other factors may include temperature, light levels, water clarity, changing nutrient ratios, changing water levels, the presence of zebra mussels and shifts in the phytoplankton makeup in the lower Great Lakes.

Studies of the toxicological properties of taste and odour compounds are scarce. The presumption has been that, while they can produce serious aesthetic problems, they do not present a risk to aquatic organisms or human consumers of drinking water or fish tainted by them. Toxicological studies are needed. Both geosmin and MIB have been non-mutagenic in bacterial tests. Some activity was found in tests with sea urchin eggs (Nakajima et al. 1996) and geosmin and MIB have shown to be genotoxic and estrogenic to rainbow trout hepatocytes (Gagné et al. 1999) but at very high concentrations relative to environmental levels, i.e., at concentrations several orders of magnitude higher than those which produce an off-flavour in water or tainting of fish. The picture is a mixed one across different levels of test organisms, but there is the suggestion that higher aquatic organisms may be more likely to show effects, albeit at very high concentrations.

Control measures by municipal water purification plants to remove taste and odour are usually expensive. Municipalities are reluctant to implement expensive control measures when the ecological and environmental details of these compounds remain unknown. Without further identification of the sources it is difficult to undertake actions to avoid or minimize taste and odour events.

There have been recent advances in the analytical methods for MIB, geosmin and other taste and odour compounds, and presently there is a wide variety of sensitive analytical methods available. Currently, funding is needed for development of stable isotope analyses to determine biosynthesis site (terrestrial, aquatic), movement/stability of these compounds through the watershed (soil, surface/ground water) and surface waters (e.g., Niagara River, Great Lakes). Contracting out is needed for the synthesis of a particular isotopically labelled standard, geosmin-d3, since the supply from CSIRO in Australia has been exhausted. A sensitive and rapid protocol has been developed to identify and measure the aldehydes; however, these compounds are unstable and difficult to work with. Currently, there is a need to develop a method of stabilizing these compounds in field samples and during analyses.

Taste and odour problems occur in B.C. (interior); Edmonton; Calgary; Lethbridge; Prairie lakes, ponds, and dugouts; Regina; Winnipeg; lower Great Lakes; Muskoka Lakes and Quebec City.

Trends

Toxins

Algal blooms seem to be increasing but the problems are sporadic. Temperature, insolation, rainfall and water level variations and increasing eutrophication are positive factors. It is likely that the frequency of algal blooms and taste and odour problems will increase. There is a risk to health when using home dialysis treatment in areas prone to blooms. Exotic species causing increasing ecological shifts and disturbed ecosystems seem to favour blue-green algae. Shifting N/P ratios due to atmospheric deposition of N and little N retention at sewage plants will likely stimulate blue-greens and/or toxin production.

Taste and Odour

The frequency of taste and odour events is increasing particularly in the Great Lakes region. At the same time, consumers' demands for high quality water will remain or increase. Taste and odour events erode consumer confidence in municipal drinking water supplies leading to a rise in the use of bottled water. Expectations of the public are increasing due to recent publicity about the need for source protection. Water suppliers are forced to install treatment facilities at great expense that are not needed in some years. Future water sources will likely be of lower quality and this will increase demand for monitoring and treatment.

Knowledge and Program Needs

Toxins

Toxins in raw and finished water are poorly studied. Although there are some traditional problem areas, new problems in the Great Lakes are occurring despite 30 years of nutrient reductions. There is a need to discover ways to optimize treatment methods in advance of new occurrences. Methods for analysis of the algal toxins are still under development. There is a need for real-time field determination methods. Analyses are hampered because standards are unavailable for most of the 65 known microcystins as well as the other cyanotoxins. There is a need to study seasonal trends in toxin production and concentration. More baseline monitoring is needed even in non-bloom conditions to help understand factors responsible for the blooms. More work on environmental triggers and ecological shifts causing blooms of toxin-producing algae are needed. Understanding of food chain transfer, for example, mussels-gobies-bass, is needed. Training of biologists in algal taxonomy has virtually disappeared and this will hamper efforts to understand the problems. Monitoring is needed to determine whether the presence of toxin spikes may increase overall exposure relative to sporadic grab sampling information. There is a need for methods validation and development. The significance of toxin binding to tissue needs to be found. Studies on the connection between toxin production and taste and odour problems are needed.

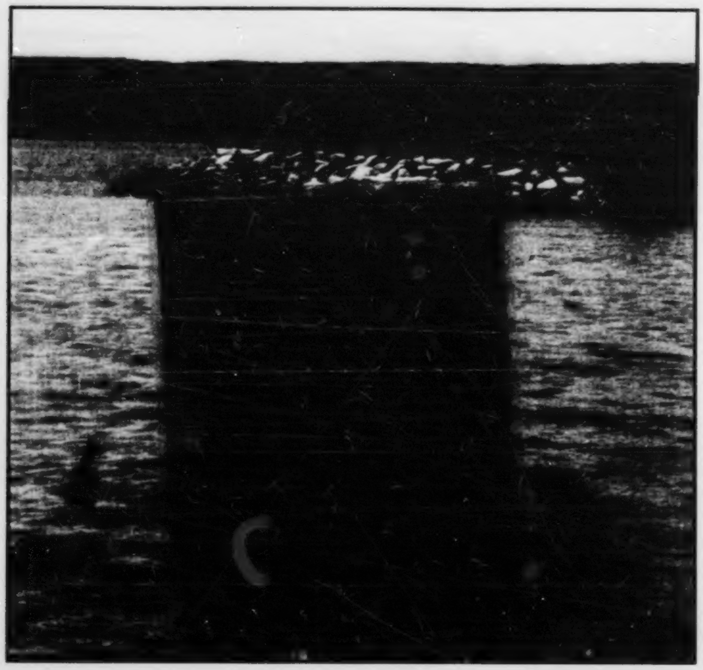
Algal toxins may be stressful especially for species not adapted in disturbed or artificial areas. At the moment it is not known whether the effects are due mainly to toxins dissolved in water or in the algae. Some of the toxins are contact irritants and their role and relevance in recreational waters is unknown.

The best way to monitor using either cell counts or toxin analyses is not known. The effects of basin hydrology and surface water movements on the generation of algal species that contain toxins needs further study. Potential effects of climate change are likely to increase the problems but this needs further knowledge. Not all blooms are toxic and the reasons for initiation of toxin production need to be discovered. Treatment methods to eliminate threats to drinking water need to be developed so the algal cells are not lysed or stimulated to release contained toxins.

Taste and Odour

There is a fundamental lack of knowledge on biological sources and triggers to production of taste and odour compounds. Little is known of the chemistry and biological fate, place of production, volatility, degradation, bio-accumulation, fish tainting, and effects on food processing. Problems in the Great Lakes have occurred despite lowered nutrient levels. The increased presence of the compounds in certain water bodies may signal synoptic changes to the ecosystem. Hypotheses about the potential for further nutrient controls to decrease the frequency and extent of events need to be tested. The potential links to UV radiation, climate change, zebra mussel populations and water level variations need to be investigated. Potential health effects due to exposure via consumption, dermal, and inhalation contact should be checked. Structure activity relationships should be investigated to determine whether toxicity effects are expected. Treatment of taste and odour problems is effective at some water plants and less effective at others. Treatment technologies are expensive and need to be optimized. Predictive models in the short and long term are needed to predict taste and odour events. The potential for Chrysophyte and Haptophyte species to cause problems in the Great Lakes need to be investigated. Some work has been published on toxicology to organisms from bacteria to rainbow trout hepatocytes. Is the existing work sufficient in the light of exposure analysis or is further testing warranted with mammalian systems and/or human cell lines? What is the biological function of these compounds: are they produced for a purpose or metabolic waste?

- Re-establish basic ecological knowledge capacity, for example, algal taxonomy to identify sources.
- Increase capacity for real-time toxin determination: assist in methods development/standards production (capitalize on existing Canadian strengths).
- Increase knowledge of environmental triggers and management possibilities for algal biomass, toxin and taste/odour production towards protection/remediation.
- Develop predictive models of toxin/taste/odour production.
- Increase knowledge on chemistry, chemical and biological fates, e.g., volatility, degradation, bioaccumulation.
- Increase knowledge of health effects of taste and odour compounds and novel biotoxins (consumption, dermal exposure, inhalation).
- Provide an appropriate level of public awareness that will reduce exposure to toxic waterblooms and prevent undue public concern when it is not warranted.



Toxic blue-green algae bloom in Hamilton Harbour, Ontario, August 2001.

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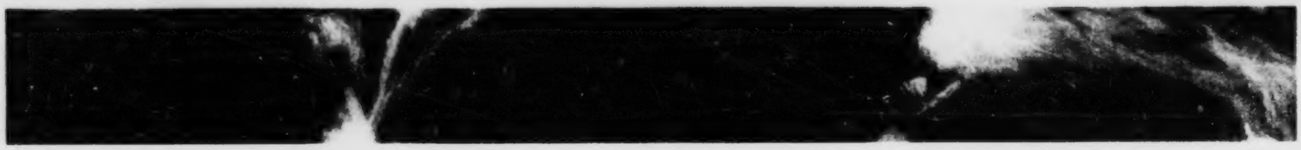

3. PESTICIDES

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Current Status

Natural pesticides such as certain botanicals, sulfur and arsenic have been used by humans for thousands of years. However, it was not until about twenty years after the introduction and widespread use of the synthetic chlorinated pesticides in the 1940s and 1950s that serious environmental problems began to be noticed. The publication of Rachel Carson's book *Silent Spring* in 1962 described the effects of some chlorinated pesticides, and arguably marked the beginning of the environmental movement.

Although pesticides form a subset of what are commonly known as toxic chemicals, they are unique in the sense that, unlike other toxic chemicals, they are deliberately applied to the natural or constructed environment. Pesticides are used extensively because of their benefits to different sectors of society and thereby to consumers, and, for example, in protecting public health. From an agricultural perspective, pesticides are intended to increase crop yields and farming efficiency, decrease loss of food during transport and storage, and ensure a stable and predictable food supply. Societal concerns, scientific advances and regulatory pressures have driven and continue to drive some of the more hazardous pesticides from the marketplace. Synthetic organic insecticides traditionally associated with broad non-target effects, with potentially hazardous residues, and with exposure risks to applicators are expected to have decreasing market share (U.S. National Academies of Science 2000). This trend has been promoted by regulatory changes that restrict the use of older chemicals and by technological changes that lead to competitive alternative products. With intensive monoculture, society will always be faced with pest control problems. We have made advances in integrated pest management in some areas, and we are developing less hazardous pesticides, biopesticides, and crops that are genetically modified to resist pests. Nevertheless, for the foreseeable future we will continue to be reliant upon chemical pesticides.

Since the environmental effects of organochlorine pesticides first became apparent, there has been an evolution in pesticide use from organochlorines to organophosphate pesticides to carbamates to pyrethroids and beyond (including natural pesticides)—in general with decreasing persistence and increased specificity toward target pests. A consequence of this development is that, in general, there are fewer effects to non-target organisms. Nevertheless, because of their widespread use and the continuing evolution of their chemistries, pesticides still pose a threat to water quality and aquatic ecosystems (e.g., U.K. Environment Agency 2000). One way of ensuring protection of aquatic systems and resources is through scientifically sound risk assessments, in conjunction with good risk communication. However, it is necessary to have sufficient capacity in research and monitoring in order to support the risk assessment process. In addition, in Canada environmental health risk assessment and communication in relation to pesticides needs to be better developed.

It should be noted that there are many connections between pesticide issues and those of other topic areas which are being considered (e.g., groundwater issues, endocrine effects, urban runoff, persistent organic pollutants, climate change). It is important to realize the relative risk of pesticides compared to other stressors. For example, the U.S. Environmental Protection Agency (1990) investigated the impairment of water quality in streams, and found the following declining order of importance of stressors: siltation (42%), nutrients (28%), pathogens (20%), organic enrichment (15%), metals (12%), pesticides (10%), suspended solids (7%) and salinity (4%).

There are about 550 pesticide active ingredients currently registered under the *Pest Control Products Act*, and the Pest Management Regulatory Agency (PMRA) registers 10 to 15 new actives each year. Perhaps 80% of pesticides used in Canada are used for agricultural purposes. The remaining 20% are used in urban areas or as material preservatives, antisapstains, heavy-duty wood preservatives, slimicides, antifouling agents, aquaculture pesticides, and so forth. PMRA has undertaken the task of re-evaluating, over the next few years, about 400 pesticides that were registered before December 31, 1994. PMRA has reviewed comprehensive databases on the remaining 150 pesticides. PMRA expects to have re-evaluated most organophosphorous pesticides by the end of 2001, and has recently announced a re-evaluation of lawn and turf pesticides. Chemical classes like the carbamates and synthetic pyrethroids will follow.

In Canada we currently lack a systematic, coordinated, interjurisdictional system for monitoring pesticides in aquatic systems (both water and sediment). At present our database in this respect is poor. This lack of monitoring data diminishes our ability to identify problematic or potentially problematic chemicals, and/or to identify areas that may be threatened. In part, this lack of data is due to the lack of coordination between provincial and federal authorities. Available data indicate that there are a number of problematic current use pesticides that are persistent, mobile and potentially toxic (e.g., lindane, endosulfan and others).

Trends

The use of chemical pesticides will continue to be a key component in pest management. New chemical pesticides will continue to be registered and introduced to the market. These will use existing chemistries and will likely include novel chemistries (e.g., the sulfonylureas, imidazolinones and strobilurins in recent years).

Biocontrol techniques have been effective for imported pests and controlled environments (e.g., beetles used against purple loosestrife) and in inundative release of biocontrol agents in greenhouses, but their long-term prospects and importance are uncertain.

The future market share of genetically modified (GM) crops with insecticide-resistant genes or herbicide-tolerant genes is difficult to estimate at this time because of public concerns about GM crops, especially in Europe. It may become significant. Although the use of GM crops may result in reduced use of traditional chemical pesticides, it may also pose some unique threats (see below), and it may result in alterations in the use of traditional chemical pesticides (e.g., McHughen 2000).

Groundwater and surface water contamination by pesticides will likely continue, and perhaps intensify because of changing land use practices and the discovery of hitherto unknown groundwater contamination that often takes years to be detected. It is difficult to anticipate trends because of a lack of monitoring data.

Emerging Issues

Changing agricultural practices may change pesticide use patterns. For example, the use of GM crops with genes to produce insecticides, or GM crops with herbicide-tolerant characteristics can increase or decrease the amount and even type of pesticides used. One tool to track changes in agricultural practices is the use of geographic information systems (GIS) and remote sensing databases, but further development is needed (an example would be the overlay of patterns of crop production, pesticide use and factors such as climatic events to identify areas most at risk of pesticide runoff to water courses following extreme events). GIS databases could also be used to identify and map vulnerable groundwater.

Climate change may change cropping practices in Canada. It may allow crops to be planted in areas hitherto unsuitable, with a requirement for pest control. Climate change may also result in changes to demands for fresh water through increased use of irrigation, with the attendant risk of contamination of this water by pesticides. Alternatively, in areas receiving more precipitation there can be a need for increased use of fungicides, as has occurred in the last few years in certain parts of the Prairies. Climate change may result in the introduction of new pests to Canada, and may require the increased use of pesticides for control. The spectrum of the pests being controlled and the pesticides used may change.

The introduction of new pests to Canada is always a threat. Such introductions often require pesticide use for control (e.g., potential spraying of mosquitoes to control West Nile virus). "Emergency" spray operations may have unintended consequences. For example, there was a large kill of lobsters in Long Island Sound close to New York City attributed to pesticides used there in the West Nile virus mosquito eradication program in 1999.

There are issues with regard to pesticide use in greenhouses. Pesticide-containing effluents from greenhouses are often untreated. Sound management practices need to be established.

The threat to water quality and human health from pesticides in urban areas (i.e., through urban runoff) has received more attention recently. This is in part fueled by actions in the U.S.A. to ban or severely restrict certain pesticides (e.g., U.S. Environmental Protection Agency 1999). PMRA has developed a "Healthy Lawn Strategy" and announced the re-evaluation of eight of the most frequently used lawn and turf pesticides (chloropyrifos, diazinon, malathion, carbaryl, 2,4-D, MCPA, mecoprop and dicamba).

Knowledge and Program Needs

We need to know the state of the environment with respect to pesticide residues. This can be accomplished by targeted monitoring geared to the assessment of risks by Environment Canada, which would feed back into the regulatory process of re-evaluation or special review by PMRA.

Little is known of the toxicological significance of constant exposure of aquatic organisms to low levels of chemicals. Little is known about the more subtle sub-lethal effects of pesticides, for example, on behaviour or the immune system. We need to know the consequences of these effects at population and community levels. We need to work towards linking effects at the biochemical level to organism health, thence to population health.

Additional research is needed on the level of effects and the potential for recovery at different levels of the ecosystem following episodic exposures to pesticides.

Little is known about the potential effects of mixtures, yet pesticides are often applied as mixtures and certainly are found in the environment as mixtures. Little is known of the cumulative effects of multiple stressors in aquatic systems. There may be combinations of physical, chemical and biological stresses occurring in aquatic ecosystems (e.g., extreme rain events washing both soil and pesticides into aquatic ecosystems).

The move towards probabilistic risk assessment methods will require some research support (e.g., fate, exposure mechanisms, and exposure data), but it is difficult at this time to identify requirements. Mesocosm experiments may be important validation tools here. There is also a great need for targeted monitoring data (in water, sediment, and biota) to validate models and methods used in aquatic risk assessments.

In general, the issue of pesticides in sediments has received little attention compared to pesticides in water. Sediments may serve as both a sink and a source of pesticides, particularly those that are lipophilic (i.e., those that have high octanol-water partition coefficients). There are implications with respect to desorption and resuspension affecting water quality, effects on benthic organisms, and the possibility of bioaccumulation to pelagic organisms.

Groundwater and surface water contamination by pesticides will continue, and perhaps intensify. It is difficult to anticipate trends because of a lack of monitoring data. Various distribution and transport models exist (e.g., the Groundwater Loading Effects of Agricultural Management Systems—"GLEAMS"—U.S. Department of Agriculture 1996), but many also require validation.

We need to determine hazards to non-target organisms of genetically expressed pesticides in crops and eventually in forestry. For example, what is the biological availability and environmental fate of genetically expressed pesticides in plant parts left on fields after harvest?

In addition to research characterizing effects, research, development and validation of appropriate models is needed to characterize inputs of pesticides (or other chemicals) into aquatic systems. Although a number of models have been developed to address the inputs resulting from traditional agricultural uses of pesticides, models to address inputs from other types of uses (e.g., antifoulants, urban and industrial stormwater discharge, aquaculture) are currently lacking.

- It is recommended that the federal government invest in the targeted monitoring of pesticide residues in environmental media (water, sediment, biota) to determine trends, assess hazards, and when warranted, provide for regulatory review.
- It is recommended that the federal, provincial and territorial governments cooperate in the development of a systematic and coordinated interjurisdictional system for the collection of pesticide use data and data on environmental concentrations of pesticides.
- It is recommended that the federal government invest more in research into risk assessment methodologies used in aquatic risk assessment. Research should include fate characterization methods (e.g., modelling) and effects characterization methods. Environment Canada should develop a program dedicated to such an activity. (It should be noted that the Canadian Network of Toxicology Centres has such a group, the Risk Assessment Methodologies group, but there is a need for similar expertise in government.)
- It is recommended that ecological risk assessment methodology for pesticides be refined, such as in the use of probabilistic methods and advanced exposure modelling. The federal government should harmonize aquatic risk assessment methodologies across Departments.
- It is recommended that there be research to improve sustainable decision-making by regulators, i.e., research to help determine what constitutes adequate levels of protection at various levels in aquatic ecosystems.
- It is recommended that there be research into the effectiveness and viability of risk mitigation and risk management options for protecting aquatic systems (e.g., use of vegetated filter strips, riparian zones). The creation of riparian buffer zones to control non-point source pollution has been widely applied in the U.S.A. but has only recently been given serious consideration in Canada (in Prince Edward Island). This practice involves the loss of arable acreage, for which farmers are compensated.
- It is recommended that more research be carried out on analytical methods for environmental residues of pesticides applied at low levels (e.g., grams per hectare), and on methods of analysis for chiral pesticides. Newer techniques of molecular biology (e.g., DNA microarrays, PCR amplification, etc.) hold promise for both the analysis of pollutants such as pesticides and the determination of effects at the molecular level; more research should be invested in such areas.
- It is recommended that more research be carried out on the fate and effects of pesticides in the aquatic environment in order to identify emerging issues.
- It is recommended that links between environmental research scientists and risk assessment scientists (regulators) be strengthened in order to provide for the timely exchange of information and expert opinion.
- It is recommended that the communication of risks of pesticides to human and ecological health be improved.
- It is recommended that Canadians be encouraged and educated to use pesticides in a more sustainable fashion by more widespread adoption of integrated pest management and integrated crop production techniques. Apart from reducing use, this will have the additional benefit of avoiding the promotion of pesticide resistance.

Groundwater and surface water contamination by pesticides will likely intensify in the future, necessitating a better understanding of their sources, fate and effects, and degradation products.

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4. PERSISTENT ORGANIC POLLUTANTS AND MERCURY

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Current Status

Persistent organic pollutants (POPs) comprise a group of chemicals that degrade slowly in the environment, bioaccumulate and have toxic properties. Many are semi-volatile and thus subject to long-range atmospheric transport and exchange among media (air, water, soil, vegetation). Various initiatives have arisen to control or eliminate POPs on regional and global scales, the most recent and widely publicized being the Global POPs Protocol, signed in Johannesburg in December 2000. Signatories of the protocol agreed to a global ban of 12 chemicals, which included organochlorine pesticides, industrial chemicals and products of incomplete combustion (Table 1). Canada is also a signatory to the UN ECE POPs protocol which lists 16 chemicals (the UNEP 12 plus 4 others) for a phase-out by countries of western Europe including Russia, Canada and the U.S.A. (Table 1).

Table 1. Current UN ECE and UNEP POPs list

Pesticides	By-products	Industrial chemicals
Aldrin/Dieldrin	PCDDs	Hexabromobiphenyl*
Endrin	PCDFs	PCBs
DDT/DDE	PAHs*	
HCH/Lindane*	HCB	
Chlordane		
Heptachlor		
Chlordecone*		
Mirex		
Toxaphene		

**Indicates not on UNEP list.*

Mercury on the other hand is a natural element. In many ways mercury behaves like a semi-volatile organic compound. It occurs in small amounts in coal and other fossil fuels, in municipal garbage, notably from electrical apparatus, and in sulphide ores. When municipal waste, coal or other fuels are burned, or when ores are smelted, mercury is driven off as a gas to the atmosphere. Once in the atmosphere, it can move thousands of kilometres with moving air masses before being oxidized to a charged species and scavenged by precipitation. Mercury is of concern because in its organic form as methyl mercury it is a neurotoxin. As a signatory to the UN ECE LRTAP protocol on heavy metals, Canada is committed to reduce mercury emissions from industrial and waste sources.

The by-products of combustion on the POPs list include PAHs (polycyclic aromatic hydrocarbons), and polychlorinated dioxin/furans. Canada has committed to reduce emissions of these compounds under the UN ECE protocol. Like mercury, the PAHs and PCDD/Fs have anthropogenic and natural sources. The primary anthropogenic source of PAHs is from combustion of carbon-based fuels that are burned with insufficient oxygen. Natural sources like fossil fuels and combustion of wood and peat have existed for millions of years. PAHs generally do not have a high acute toxicity but several of them are potent carcinogens. The PCDD/Fs are by-products of synthesis of many chlorinated organic chemicals, e.g., chlorophenols, and in chlorine bleaching of wood pulp, however, these sources have been greatly reduced during the 1990s.

Trends

Substantial reservoirs exist for many POPs in the Canadian environment due to historical usage stretching back to the 1930s and 1940s. For example, organochlorine pesticides contaminate soils in agricultural regions, sediments in remote lakes sprayed for insect control, and in the urban environments treated for insect pests. PCBs are present in urban and rural soils, landfills and contaminated industrial sites. The same situation exists in most developed countries in the northern hemisphere. Also, Russia continues to use PCBs for electrical equipment. Limited usage of DDT for malaria control is still permitted under the Global Protocol. Other OC pesticides are still applied in Mexico, Central American, African and Asian countries. Mobilization from these reservoirs will continue to supply POPs to the atmosphere on a regional and hemispheric scale, even after current usage is stopped.

Atmospheric transport and deposition is a major pathway of contamination of aquatic environments by POPs and mercury in Canada. POPs and mercury (Hg) are routinely found in air and precipitation throughout Canada based on measurement programs in the Great Lakes region, the Rocky Mountains, and in the Arctic. Thus water quality concerns for these chemicals must include consideration of the input from and the escape to the atmosphere.

Mercury is transported through the atmosphere almost entirely as gaseous, elemental mercury. As such, it is only slowly removed by rain and snow and so has a low rate of deposition. Recent research in the Canadian Arctic has shown deposition of mercury occurs as polar sunrise releases bromine from sea salts where ionic bromine has accumulated over the winter. Thus, the unique photochemistry of the Arctic conspires to produce a form of mercury, which is quickly deposited from the atmosphere onto the snow pack. A critical—and so far unexplored—link is transfer of the deposited mercury to the food chain.

Concentrations of PCBs, DDT and other persistent organochlorine pesticides remain high in many aquatic food webs in Canada as a result of emissions from old sources and from long-range transport and deposition. In the Great Lakes region, levels of PCBs and DDT have declined significantly in top predators. For example, continued decline in PCBs in herring gull eggs reflects lower emissions following controls on open uses. Declines in Great Lakes lake trout and walleye have not been as dramatic especially since the mid-1980s reflecting continued emissions from urban areas and recycling of contaminants within the lakes (Pierce et al. 1998). There are very limited time-trend data for POPs in fish outside of the Great Lakes. In the Arctic, significant declines of PCBs and DDT have been observed in seabirds (Braune et al. 2001) but the story is mixed in the case of marine mammals. Significant declines of DDT have been found in ringed seals since the early 1970s (Addison and Smith 1998) but not for PCBs in blubber of beluga from southeast Baffin Island over the period 1982 to 1996 (Stern and Addison 1999).

Despite the declining levels, the interim guideline for PCB of 0.32 ng TEQ/g ww, designed to protect Canadian wildlife that consume fish and shellfish (Environment Canada 1998) is routinely exceeded by both predator and forage fish in many areas. Also, PCB levels in surface waters in many small rivers draining urban areas regularly exceed the 1 ng/L EQG. In the case of methyl Hg, the interim guideline of Hg of 22 ng/g ww for protection of fish consuming wildlife is exceeded in almost all fish measured to date in Canada. In Ontario, 95% of fish consumption advisories in lakes are due to Hg with the remainder due to PCBs and toxaphene (OMEE 1997). In Kejimkujik National Park in Nova Scotia loons' elevated levels of Hg have been associated with reproductive effects (Evers et al. 1998).

Experience from the Great Lakes and the Arctic suggests that for communities with high fish consumption, such as Aboriginal communities on remote Canadian Shield lakes, even relatively low levels of POPs and Hg will result in exceedances of Tolerable Daily Intakes (Jensen et al. 1997). Numerous studies of fish consumers in the Great Lakes region (recently summarized in Johnson et al. 1998) suggest that exposure to contaminants via high rates of fish consumption causes disturbances in reproductive parameters and neurobehavioural and developmental deficits in newborns and older children. There are insufficient data with which to assess if people in other regions of Canada who also rely on country foods, especially fishes, will exceed TDIs. With the exception of programs run by the Ontario Ministry of the Environment there are no current provincial or federal contaminants survey programs that address this information gap.

Levels of mercury, unlike the PCBs and DDT, have increased in the past 20 years in fish-eating birds and mammals. A striking example is the twofold increase from 1975 to 1995 observed in mercury in thick-billed murre eggs in the Canadian High Arctic (Braune et al. 2001). Another, independent line of evidence that mercury inputs to remote locations have been increasing comes from profiles in sediment cores. These also infer that inputs have increased greatly relative to pre-industrial times.

Emerging Issues

With the development of regional and global agreements to ban POPs, the attention of regulators and researchers has turned to other chemicals with similar properties. The UNEP and UN ECE lists are not closed. New substances can be added if they meet the scientific criteria for inclusion and if ratified by the signing parties. The Evaluation Division of CCEB has recently prepared a list of 100 chemicals in use in Canada that, in the opinion of an expert panel, may meet criteria for persistence, toxicity and in some cases bioaccumulation (Table 2). The criteria for inclusion are based on Canada's Toxic Substances Management Policy (Environment Canada 1995) and include evidence for transport to remote regions, long persistence in water, soil or sediment, octanol-water partition coefficients >5000 and potential toxicity.

Table 2. EC-CCEB listing of top 100 potential POPs in current use in Canada

Classes	N	PB & T*	Examples
Pigments & dyes	16	13	halo-, methoxy substituted PAHs and heterocycles
Chlorinated substances	13	3	lindane, atrazine, PCP
Antioxidants	7	5	thiol- and amino-substituted benzenes
Nitro substances	1	1	trifluralin
Brominated flame retardants	16	9	BDPEs, brominanted cycloalkanes
Musks	6	5	musk ketone, musk xylene, poly-cyclic musks
Phthalates	7	0	cyclohexyl, nonyl, tridecyl
Miscellaneous organics	27	18	terphenyl, imidazoles, S- and N-substituted biphenyls
Perfluorinated carboxylates	4	4	PFOA, PFDA
Perfluorinated sulfonates	3	3	PFOS, PFOSamide
Total	100	61	

**Number of compounds that may be persistent, bioaccumulative and toxic.*

With the exception of two or three pesticides on the list in Table 2, there is very limited information available on the physical properties, half-lives of persistence or bioaccumulation of these compounds, or on current environmental levels. This is a major problem with efforts to identify and measure chemicals other than those on the current POPs list. While there are environmental measurement data on some pesticides listed in Table 2, as well as phthalates, musks, and brominated flame retardants, the vast majority of the 100 compounds remain unstudied in Canada and elsewhere.

Studies on brominated flame retardants (BFRs), perfluorocarboxylates and sulfonates have recently begun in Canada with funding from the Toxic Substances Research Initiative. The work on BFRs has shown that polybrominated diphenyl ethers (PBDEs), additives used in the manufacturing of plastics, paints, textiles and electrical devices, are increasing rapidly in the environment. For example, temporal trend data for PBDEs in gull eggs from Snake Island in Lake Ontario show an increase of 65-fold between 1981 and 1999; and lake trout from Lake Ontario showed a 300-fold increase in PBDEs between 1978 and 1998.

The presence of perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) in liver samples of top predators, such as polar bears and fish-eating birds, as well as in human blood samples, was recently reported by the manufacturer, 3M Company. These compounds are anions and have low octanol-water partition coefficients. However, they persist in biota because of the great stability of the perfluoro group and because they are recycled in the entero-hepatic circulation. This new bioaccumulation pathway may be important for a wide range of chemically stable, polar compounds, and this raises the issue of whether criteria for identifying POPs will have to be modified.

Not included on the list are two groups of chemicals, the polychlorinated naphthalenes (PCNs) and chlorinated paraffins which resemble current POPs in terms of physical properties and molecular structure. PCNs were first manufactured for industrial purposes in the early 1900s until 1977 in the U.S.A. They are of concern because several congeners elicit dioxin-type responses similar to co-planar PCBs. PCNs are also a by-product of combustion and analyses of dated sediment cores show increases of combustion-related PCNs in recent layers. Combustion-derived PCNs are also evident in air samples from the Toronto area and the Great Lakes. Chlorinated paraffins are another complex group of chemicals with physical properties similar to many chlorinated pesticides. Short-chain chlorinated paraffins (SCCPs) have been proposed for virtual elimination in Canada under CEPA Track 1. SCCPs are detectable in the Canadian environment including remote lake sediments and marine biota in the Arctic. However, highest levels are found in biota and sediments near urban areas. Like the PCNs, SCCP concentrations in the environment appear to be declining based on profiles in dated sediment cores.

Recent studies have found that halogenated phenolic compounds (HPCs), including pentachlorophenol (PCP), hydroxy-substituted PCBs (OH-PCBs) and hydroxy-brominated diphenyl ethers are present in the blood of marine mammals and humans in Canada from the Arctic and temperate regions of North America (Sandau et al. 2000). HPCs have been shown to have endocrine disruption potential based on in vivo and in vitro assays (Kester 2000; Schuur et al. 1998), while OH-PCB sources may be primarily from metabolism of other PCB sources.

Several persistent current use pesticides (PCUPs) such as those identified in Table 2 also have characteristics which lead to persistence and long-range transport. Endosulfan and lindane can be detected in freshwater and marine biota throughout Canada even in sites far removed from use areas. In general, there is no monitoring of other potential PCUPs in fish. Additional possible candidates are dacthal, pentachlorophenol, trifluralin and related dinitroanilines. Other studies have shown that the herbicide trifluralin is detectable in arctic snow and that dacthal, widely used as a fungicide in the U.S.A., is detectable in air at Alert in the High Arctic and at Tagish, Yukon, with highest levels during the summer months (D. Muir, unpublished data, NWRI, Burlington, ON).

Knowledge and Program Needs

Data are needed on the toxicology of individual compounds of POPs, e.g., bioaccumulative components of toxaphene. Current lack of data makes risk assessment of actual environmental residue problematic. For example, Health Canada has assigned large safety factors for TDIs for chlordane and toxaphene due to lack of data—we may be overstating the concern for chlordane and toxaphene contamination as a result.

Basic information is needed on the mammalian, avian and aquatic-toxicology of new POPs, i.e., typically limited to LD_{50} in one species.

Basic physical property information is needed on "new" POPs such as those on the EC-CCEB list, especially at temperatures relevant to Canada, in order to predict environmental fate and bioaccumulation potential. Presently, K_{ow} values are only available based on structure activity. Biodegradation, photolysis and hydrolysis data, which are needed to predict overall environmental persistence and LRTAP potential, are lacking for most new POPs.

Modelling capability for forecasting the trends in environmental levels and fate of old and new POPs needs to be refined. This may require new approaches for modelling as well as physical-chemical property data.

Analytical methods information is needed for new POPs. For example, published analytical methods are unavailable for 80% of the compounds on the EC-CCEB top 100 POPs list. Method development is limited by lack of facilities such as clean rooms to limit contamination from products in current use as well as lack of appropriate instrumentation.

There is limited knowledge available on current levels and trends of old and new or potential POPs in all environmental compartments, especially aquatic and terrestrial. This makes exposure and risk assessment for new chemical exposures difficult—relying solely on Predicted Environmental Concentrations (PECs) that are based on limited phys-property data.

The lack of knowledge of anthropogenic versus natural sources of mercury, and their relative biological availability, continues to be a problem in the assessment of mercury in the Canadian environment.

The biological implications of total mercury concentrations in biota need further investigation. Current assessment methods assume all mercury can be converted to methyl mercury. The extent of conversion of various forms of mercury, i.e., selenides, inorganic mercury, organic species, to methyl mercury is unknown.

Detailed investigations of the mercury biogeochemical cycle are needed to understand the transfer of mercury from the atmosphere to aquatic food webs. Also unknown is the reverse cycle of mercury: how much is reduced to elemental mercury in snow and on terrestrial surfaces and volatilized again?

PAHs represent a major contaminant group in Canadian surface water but much more information is needed on PAH levels in biota where PAHs are present as epoxides and hydroxylated derivatives. In general, there is a need to develop a better understanding of these by-products in the environment.

Assessment of time trends in POPs resulting from UN ECE and UNEP agreements is limited by lack of commitment to long-term research and monitoring programs. At present there are long-term air and precipitation programs (MSC/IADN) and one on fish

(Great Lakes, DFO) and one on fish-eating birds (CWS). There are other smaller ad hoc efforts by individual scientists for temporal trends using biota or sediment cores, e.g., funded by NCP, TSRI or NREI. There are no long-term trends measurements for POPs or new POPs in surface waters.

The knowledge gaps identified for POPs and mercury need to be addressed.

A research and monitoring program on POPs with a national focus is needed that ensures that information on current levels and time trends of old and emerging POPs are available in all regions in major environmental media, e.g., water, air, sediments and fish.

Development of capacity (instruments, clean room facilities, trained personnel, etc.) within Environment Canada to precisely measure stable isotopes of heavy metals, a promising technique for identifying sources possibly including proportions of anthropogenic versus natural mercury and other metals in widespread commercial use.

Development of capacity (instruments, clean room facilities, trained personnel, etc.) to measure new POPs and PCUPs in environmental samples within Environment Canada and within other government and university labs.

The capacity to link the chemical measurements to biological effects needs to be strengthened through additional funding for long-term field studies, and support for training.

A trapper with the Holman Society, fishing for lake trout and arctic char through the ice on Uyaaktuk Lake near Holman, Northwest Territories. Studies show exposure to contaminants through high rates of fish consumption causes disturbances in reproductive parameters and neurobehavioural and developmental deficits in newborns and older children.

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5. ENDOCRINE DISRUPTING SUBSTANCES

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Current Status

There is growing concern internationally about environmental risks posed by endocrine disrupting substances (EDS). These chemicals include a wide variety of environmental contaminants that can exert a diverse array of effects on growth, development and reproduction in biota. The effects may occur at extremely low concentrations and be expressed in following generations well after the original environmental exposure. These subtle effects may be extremely difficult to detect, even though they may have significant impacts on populations and ecosystems. Although reproduction and development are major endpoints for environmental and human health assessments in many federal government programs, current assessment approaches may not be adequate to detect subtle impacts mediated through disruption of endocrine systems. Development of screening and testing programs for endocrine disrupters in the United States, and international agencies such as the OECD, have been initiated and may have a profound influence on how Canada will address this issue in the future. It is critical that Canada be proactive, identify and address knowledge gaps from a Canadian perspective, and anticipate international developments that may influence Canadian policy.

Concerns over the potential impacts of substances that disrupt endocrine function in biota in the Canadian environment led to CEPA 1999 making research on "hormone disrupting substances" a Ministerial duty for both Environment Canada and Health Canada (*CEPA 1999 article 3, subsection 44[3]*). Numerous drugs, pesticides, industrial chemicals, metals and natural compounds detected in the environment may alter the normal function of endocrine systems (National Academy of Sciences 1999; Di Giulio and Tillitt 1999; Kendall et al. 1998). Recent studies have implicated some of these substances in the alteration of aspects of growth, reproduction and development of animal species, including humans in Canada and other areas of the globe (Foster 2001; McMaster 2001). It has been suggested that such changes may be associated with adverse responses in individuals or populations of organisms, although further research is needed to substantiate this linkage (Munkittrick 2001; Van Der Kraak 2001; National Academy of Sciences 1999). Chemicals suspected of having endocrine disrupting capability include a wide variety of chemical classes and mixtures (Hewitt and Servos 2001); thus there are implications for a large number of activities and programs in the federal government (Servos et al. 2000a).

Trends

The EDS issue has evolved rapidly and there is increasing public pressure to take action to reduce the potential risk of EDS in the Canadian environment. The uncertainty surrounding the potential for serious and nonreversible effects has resulted in the EDS issue being linked to the debate over the precautionary principle in Canada as well as other jurisdictions (Commission of the European Communities 1999, 2000). CEPA 1999 commits the government to implementing the weight-of-evidence approach as well as the precautionary principle in decision making (*Preamble CEPA 1999; paragraph 2[1][a]*). It has been recognized that we must be proactive so that we reduce uncertainty and make decisions based on sound science (Servos and Luce 1997; Servos et al. 2000a). The EDS issue presents new challenges for scientific assessments of industrial chemicals (Sutcliffe 2001; Servos 2001), pesticides (Moase and Delorme 2001) and the Canadian environment (Munkittrick 2001).

There are also numerous international activities related to the EDS issue that have implications for Canada. The requirement in the United States to develop an approach for screening and testing for endocrine disrupting substances by the summer of 2000 has resulted in numerous activities in that country (US EPA 1997). The OECD, in which Canada is an active partner, has initiated a program to harmonize testing and screening on EDS (OECD 2000). The EU has recently published a strategy for endocrine disrupting substances and published a list of potential endocrine disrupting substances for further testing in the immediate future (Commission of the European Communities 1999). It is expected that EDS will continue to be a high-profile international issue.

Emerging Issues

Prompted by the urgency and complexity of the question, the Five Natural Resources Departments Working Group on Endocrine Disrupting Substances (5-NR EDS WG) hosted a multi-departmental, multi-sector workshop to address emerging issues associated with scientific assessment of EDS in the Canadian environment. The Workshop's agenda placed a major emphasis on reviewing the current status of science on the EDS issue in Canada, but also considered how the issue fits within the regulatory framework of the federal government. The following is a summary of the major conclusions, research priorities and recommendations from the workshop held at the Grandview Inn in Huntsville, Ontario, February 13-17, 2000 (Servos et al. 2000a).

Endocrine Disrupting Substances in the Canadian Environment

There is a concern in Canada that low level and/or multigenerational effects, possibly mediated through disruption of normal endocrine function, are occurring and are currently going undetected. Effects on development and reproduction have been observed in wildlife in Canada, including: deformities and embryo mortality in birds and fish exposed to industrial chemicals or organochlorine insecticides, impaired reproduction and development in fish exposed to pulp and paper mill effluents, abnormal development of molluscs exposed to antifouling substances (TBT) applied to the hulls of ships, depressed thyroid and immune functions in fish-eating birds in the Great Lakes, and feminization of fish exposed to municipal effluents. Available data suggest a potential for these types of effects to occur in humans, although there is only circumstantial evidence that they occur in response to environmental contamination. For example, studies on mother-infant cohorts exposed to environmental contaminants through high consumption of contaminated fish suggest that there can be cognitive and neurobehavioural effects in infants due to prenatal exposure. Some of the effects identified may not occur directly through an endocrine mechanism, or in some cases the mechanism is not yet known; however, this does not diminish the importance of effects or observations. Attention should therefore focus on functional endpoints of growth, reproduction and development during critical life stages, rather than on a specific mode or mechanism such as receptor-mediated responses. In light of relatively recent results, traditional ecosystem monitoring and to some extent human health monitoring programs have not used sufficiently sensitive endpoints related to growth, reproduction and development. Existing monitoring programs should be evaluated and modified to encompass new concerns, identify new issues, and complement mechanistic and toxicology studies.

Risk Assessment and EDS in Canada

Endocrine disrupting substances can be addressed within the existing Canadian legislation and regulatory frameworks. Current risk assessment/management approaches in Canada can be used to identify effects produced via endocrine disrupting mechanisms, but subtle effects on growth, reproduction and development must also be considered. Risk assessment/management approaches require continuous improvement and need to include new tests and approaches as they become available. Both hazard and exposure are important criteria for assessing or prioritizing risks and need to be considered in risk assessments. Additional information required for risk assessments of suspected EDS, which is not normally available, includes: information on sensitive life history stages; identification of windows of sensitivity, including exposure at this stage; possible presence and significance of delayed responses or effects; and significant development of the science of assessing effects of mixtures and mixture interactions. In addition to specific chemicals, a number of sites and sectors have been identified as representing the highest risk and research should be focused in these areas.

Table 1. The following sites and sectors were considered the most important for consideration of EDS impacts in the Canadian environment (Servos et al. 2000a)

Major Sites and Sectors	
I.	municipal effluents
II.	intensive agriculture (including pesticides and livestock production)
III.	textile mill effluents
IV.	pulp and paper sector (recent dramatic improvement)
V.	mining and metals
VI.	historically contaminated sites
VII.	identified areas of concerns (e.g., Great Lakes AOCs)
VIII.	contaminants in the Arctic (including Aboriginal foods)

International Activities and Implications for Canada

International activities will continue to have major implications for the EDS issue in Canada. International harmonization is needed to ensure minimum duplication and maximum benefit to the respective countries dealing with the question, without giving up the ability to set national priorities/concerns differing from those accepted internationally. It is critical that Canada participates in international efforts so that internationally accepted tests are applicable in a Canadian context: i.e., consideration of unique aspects such as climate, population, diet and chemical use patterns.

Application of Sound Science to the EDS Issue

Potential subtle effects on reproduction and development should be considered in our scientific assessments and screens for toxic substances. While in vitro information and studies are useful, they are not currently linked directly to or predictive of in vivo responses; however, this is expected to improve rapidly with additional research. Results of laboratory testing should be related to ecological significance in the environment and possible effects in the environment, especially with respect to sensitive life stages. Functional impacts leading to a negative effect on one or more of survival, growth, development, reproduction, behaviour, immune competence or disease resistance should be monitored and assessed with concern focused at the level of the individual (in vivo) or above.

Large uncertainty is associated with scientific assessments related to the EDS issue and should be considered in developing risk management options. A weight-of-evidence approach based on the most credible information available should be used to make appropriate decisions to protect Canadians and the Canadian environment. Estrogen, androgen, and thyroid hormones are reasonably conserved across vertebrate species. However, there are many species-specific differences in how hormones are regulated and function; thus potential variability in responses of different species and large uncertainty in extrapolation among species are to be expected. Interactions with other chemicals should be considered when possible, despite the complexities and large uncertainties involved. Each federal program may have slightly different requirements but the basic principles for testing and assessment should be the same. A tiered-testing approach that considers both hazard and exposure is advantageous and should be incorporated into Canadian programs once validated and accepted internationally. Collaboration and consultation with stakeholders and the public on the issue must continue.

Knowledge and Program Needs

Knowledge gaps and research needs were identified in each of the breakout sessions during the workshop and separated into two main themes: EDS in the Canadian environment and risk assessment; and application of sound science to the EDS issue. They were summarized and then prioritized by participant voting (Table 2; see Workshop Proceedings for details; Servos et al. 2000a). It should be underlined that gaps and needs identified were specific to Canada, and considered unique aspects of Canadians and the Canadian environment, our approaches to the management of toxic substances, and our scientific expertise and capacity in this area of research (Table 2).

Canada must continue to support research to address critical knowledge gaps and ensure application of sound science to risk assessment and management of EDS in the Canadian environment. Research should continue to reduce the large uncertainty associated with scientific assessments of these types of substances and effects. Research on the fundamental reproductive and developmental biology of humans, biota and ecosystems is essential to understand and detect subtle effects on growth, reproduction, development (and ultimately effects on populations), mediated through endocrine or other mechanisms and should be encouraged. Canadian research programs should continue to focus on our traditional strengths in field studies, identifying impacts, and defining cause and effect relationships. Replication of international screening and testing activities should be minimized, and Canada should participate in international activities to ensure results are consistent and applicable to the Canadian environment.

Continued coordination and collaboration of research in government, industry, academia, and public interest groups are essential, and interaction among research and regulatory scientists in each of these groups must continue. Programs such as the Toxic Substances Research Initiative (TSRI), the Canadian Network of Toxicology Centres (CNTC) and appropriate internal government and industry programs should be enhanced and focused more on scientific assessment of EDS. Although Canadian scientists make major contributions to the EDS question internationally, the science capacity in Canada to address this issue is limited and should be expanded. Enhanced science-based monitoring programs are required to detect and evaluate the risk to Canadians and the Canadian environment from EDS. Existing monitoring programs should also be enhanced as a mechanism to detect EDS, effects and concerns in the Canadian environment.

Table 2. Knowledge gaps/research needs identified for scientific assessment of endocrine disrupting substances in the Canadian environment

Priority*	EDS in the Canadian Environment and Risk Assessment
1.	Calibrating or benchmarking the ecological relevance of EDS tests—taking them out of the laboratory and assessing their ability to detect impacts/adverse effects of EDS in the Canadian environment.
2.	Improve basic knowledge on the role of hormones in the development of nervous, reproduction and immune systems in human and relevant species.
3.	Improve understanding of role and importance of naturally occurring, hormonally active substances in the EDS issue (with regard to testing).
4.	Comprehensive guidance on how to interpret and use scientific data in risk management decision-making frameworks.
5.	Definition of acceptable risk, adverse effect.
6.	Risk communication (need to enhance current activities).
7.	Development and recognition of endpoints for early life stage effects related to organizational changes (e.g., behaviour, immune, endocrine, etc.).
8.	Improve basic knowledge about early specification and development of endocrine and reproductive organ systems from fertilization onwards in vertebrates.
9.	Correct deficiencies in exposure and monitoring data.
10.	Improved understanding of effects of EDS on invertebrates.
11.	Development of mechanistic knowledge on the link between in vitro and in vivo responses.
12.	Understanding link between (screening) test result and adverse effects.

Priority*	Application of Sound Science to the EDS Issue in Canada
1.	Establish connection between lab tests and actual world. Are tests predictive of real world effects? Are things happening in real populations that are not predicted?
2.	Linking screening/testing methods to ecological relevance (especially with respect to sensitive life stages).
3.	Development of a framework for risk assessment of interactions of EDS in mixtures and effluents.
4.	Better knowledge of exposure and dispersal of EDS in the environment.
5.	Better understanding of low dose effects and thresholds.
6.	Ability to separate effects of natural estrogens from effects of anthropogenic chemicals.
7.	Linking biomarker responses with adverse atypical effects (growth, development, reproduction).
8.	Development of a framework regarding public values for risk management decisions.
9.	Enhanced monitoring effort for effects in the environment.
10.	Better knowledge of immune system effects.
11.	Mechanistic studies, including complications from mixed agonists (estrogenic in some tissues, anti-estrogenic in others).
12.	Develop a framework for risk assessment of cumulative exposures and effects rather than single compound approach.

**Priority established by voting of all workshop participants.*

The EDS issue is broad in scope and, as a result, is linked directly to numerous other national environmental health issues and initiatives. Its complexity will necessitate a coordinated response from federal government departments, industry, academia and other organizations. Related activities in other jurisdictions, especially the United States, Japan and Europe, will influence development of public opinion and policy in Canada over the next few months and years. The following four areas should form a National Agenda for EDS in the Canadian Environment (Servos et al. 2000b).

National Leadership and Communication on the EDS Issue in Canada

A high priority should be placed on providing national leadership at the federal level on the issue of EDS in the environment. The EDS question is related directly to many other priority environmental health issues including Children's Environmental Health, POPs, CEPA, and regulation of pesticides. The issue has also been directly associated in Canada and other countries with the debate on the precautionary principle. A comprehensive and coordinated program of collaborative research, communication and regulation/policy development needs to be established. Federal departments, industry, academia and public interest groups should actively participate and collaborate in an effort to generate the knowledge necessary for scientifically sound assessments, regulations and policies. A national communications program should be established to provide scientists, policy makers and the public with current information on national and international developments and activities.

Establishing a Better Knowledge Base of the Exposure and Effects of EDS in the Canadian Environment

Canadian scientists have played an important role in EDS activities, conducting some of the most comprehensive field studies: e.g., effects of organochlorines in birds, reproductive effects in fish exposed to pulp mill effluents, and effects of chemicals on endocrine-dependent responses such as smoltification. Canadian scientists, especially in the federal government, should utilize and emphasize the traditional strengths of Canadian science and programs in assessing effects on ecosystems to maximize contributions to international efforts. Limitations on available resources dictate that research programs must be focused and prioritized to maximize their effectiveness. Research programs should emphasize development of knowledge and tools to conduct more comprehensive environmental assessments, and apply these tools in field and laboratory studies to determine the extent to which Canadians and the Canadian environment may be affected. Scientists in Canada have considerable expertise in validating the relevance of specific responses and exposures in whole animals and populations (including humans). Emphasis should be placed on determining the relevance and acceptability of internationally recognized EDS responses and tests in the Canadian population and the Canadian environment.

The federal government should give priority to assessing those sites, sectors and populations identified as having the highest potential for adverse effects on functional endpoints related to growth, reproduction or development of biota through disruption of endocrine function, as well as other, not yet fully understood mechanisms. Endocrine disruption should be considered as only one of several mechanisms by which environmental effects can be mediated. Research programs should include both previously identified issues, such as industrial effluents and priority substances, and emerging issues such as intensive agriculture (pesticides and animal wastes), urban exposure (e.g., air, sewage, runoff), and new chemicals. Collaboration and partnerships with universities and industry should be employed to further research mechanisms and other critical areas that will enable scientific assessments of EDS in the Canadian environment.

National and International Harmonization of Screening and Testing Protocols

Development of screening and testing methodologies is recognized as an important research and policy area both within Canada and internationally. Enormous efforts are currently underway in other countries to develop and validate screening and testing methods for EDS. Canadians should participate in and support the efforts of international organizations, especially the OECD, to harmonize internationally accepted screening and testing methods to address this complex global issue. However, this should not be the emphasis of Canadian research programs. Canada should work with a variety of international agencies to validate and calibrate currently proposed tests for use internationally and in Canada, and ensure their applicability to the Canadian population and Canadian environment. Duplication of the efforts of other countries should be actively avoided in order to maximize our contribution to international efforts.

Enhanced Scientific Assessment and Action on Priority Substances

Public perception of the EDS issue has evolved rapidly from scientific interest to seeking action to protect human and ecosystem health. CEPA 1999 requires research on "hormone disrupting substances" and application of both the weight-of-evidence approach and the precautionary principle to management of toxic substances in Canada. Although there are special considerations related to assessment of EDS, they can be addressed within current risk assessment/management frameworks with only minor adjustment for inclusion of new knowledge and testing protocols.

Priority substances such as PCBs, tributyltin, selected pesticides and industrial chemicals shown to have or suspected of having effects on growth, reproduction or development, possibly as a result of alterations of the endocrine system, should continue to be evaluated to determine their risk to the Canadian environment. Canada should act to implement current national or international agreements and protocols (such as the Protocol on Persistent Organic Pollutants) to reduce the exposure of these chemicals to the Canadian environment. Each federal department should take action to reduce the exposure and risk of EDS to Canada and the Canadian environment.

Research on better assessment and management tools for this class of chemicals should be conducted to reduce uncertainty and lead to more effective remedial and risk reduction approaches. As internationally accepted screens and tests are validated and made available in the next two to five years, they should be integrated into the current regulatory framework, which considers both hazard and exposure in characterization of risk and formulation of risk management options. Environmental and human health monitoring programs should be modified and enhanced to build a capability to detect exposure and subtle effects on critical developmental stages of biota and humans.

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Intensive agriculture is one of the major causes of endocrine disruption in the Canadian environment.

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6. NUTRIENTS—NITROGEN AND PHOSPHORUS

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Current Status

Nitrogen (N) and phosphorus (P) are natural resources for which there is intense competition in terrestrial and aquatic ecosystems not greatly affected by human activity. Until recently, the supply of N and P for most plants, and ultimately to animals, was limited. The most abundant N source, N gas, could only be used by plants once it was fixed by certain bacteria or algae into ammonium or nitrate compounds. Similarly, the most abundant P source, P-bearing minerals, only became available by weathering. Consequently, N or P was a limiting nutrient in most ecosystems prior to human settlement and agricultural development. Moreover, because N and P were in high demand, these nutrients were stored and recycled in close proximity to the locale from which they were scavenged. This pattern was true for plants and animals, including humans because, prior to urbanization, feces from livestock and humans along with other composted waste was returned to the soil, thereby closing nutrient recycling loops and maintaining the fertility of the soil.

The amount of N and P available for plant uptake has increased dramatically in the past several decades. The causes are a massive increase in the use of fertilizer, burning of fossil fuels, development of large urban populations, and an upsurge in land clearing and deforestation. The amount of available N has more than doubled since the 1940s, with human activities contributing 210 million tonnes per year to the global supply of N, compared to only 140 million tonnes generated per year by natural processes (Vitousek et al. 1997). Similarly, natural weathering of phosphate-bearing rocks is now overshadowed by mining activities as a source of P, with approximately 140 million tonnes of phosphate-bearing rock now mined each year (Steen 1998).

This influx of nutrients has disrupted the natural cycles of both N and P. Where animal manure and human wastes were historically spread on farmland to recycle nutrients, a "once-through" system now predominates. Thus, phosphates extracted from mined phosphate rock and inorganic N fixed from N gas by industrial processes are applied to agricultural land or fed to livestock. Nutrients in the form of foodstuffs flow from the farm to the cities, where most ultimately end up in landfill (sewage sludge, incinerator ash), or in surface or ground waters (Caraco 1993; Nixon et al. 1996). Reactive N and P released to the atmosphere as a result of agricultural practices, as industrial emissions and, in the case of N, as by-products of home heating and automobile engine combustion may be transported and deposited hundreds or thousands of kilometres from their origin.

The environmental consequences resulting from addition of bioavailable N and P to the Earth's ecosystems could be profound. Based upon our review of available scientific evidence, we are certain that N and P loading from human activity has:

- Accelerated eutrophication of certain rivers, lakes and wetlands in Canada, resulting in loss of habitat, changes in biodiversity and, in some cases, loss of recreational potential.
- Increased the frequency and spatial extent to which the drinking water guideline for nitrate has been exceeded in groundwaters across Canada and caused economic burden for those Canadians who must transport household water from off-site sources.
- Caused and continues to cause fish kills in southwestern Ontario due to ammonia toxicity.
- Contributed to the decline in amphibians in southern Ontario due to long-term exposure to elevated nitrate concentrations.
- Led to elevated risks to human health through increased frequency and spatial extent of toxic algal blooms in Canadian lakes and coastal waters.
- Contributed to quality of life concerns for Canadians through water use impairments (e.g., excessive algal and aquatic weed growth); aesthetic (taste and odour) concerns related to water supplies; and contamination of water supplies (e.g., by nitrate and by trihalomethanes [THMs] produced as by-products of disinfection of water containing organic material).

- Increased the economic burden to Canadians as a result of the need for treatment, monitoring and remediation of contaminated water.

Trends

At present, environmental problems caused by excessive nutrients are less severe in Canada than in countries with a longer history of settlement and agricultural production. This trend is due to our relatively small population compared to our land base and the protective measures implemented by both the federal and provincial/territorial governments in the last 30 years. However, while successes have been realized, environmental and human health problems related to nutrients are evident across Canada.

Household sewage is the largest point source of N and P to the Canadian environment and will likely continue to be so. In 1996, an estimated 5.6 thousand tonnes of total P and 80 thousand tonnes of total N were released to lakes, rivers and coastal waters from municipal wastewater treatment plants in Canada (Table 1). This load occurred despite the fact that, in 1996, 73% of Canadians were served by municipal sewer systems and at least 94% of the wastewater collected by sewers received primary or higher treatment. Most of the N and P in household sewage are from human waste (urine and feces). In addition to household sewage collected in sewers, septic sewage systems, urban runoff and combined sewer overflows are also major sources of nutrients to ground and surface waters. There are no national figures for losses due to leaching from municipal landfills.

Table 1. Comparison of P and N loading to Canadian surface and ground waters from various sources, 1996

Nutrient Source	Nitrogen (10^3 t/yr)	Phosphorus (10^3 t/yr)
Municipality		
- Municipal wastewater treatment plants	80.3	5.6
- Sewers	11.8	2.3
Septic systems	15.4	1.9
Industry[1]	11.8	2.0
Agriculture[2] (residual in the field after crop harvest)	293	55
Aquaculture	2.3	0.5
Atmospheric deposition to water	182 (NO_3- and NH_4+ only)	N/A

[1] Industrial N loads are based on $NO_3 + NH_3$ and are thus DIN not TN; industrial loads do not include New Brunswick, Prince Edward Island or Nova Scotia. Quebec data are only for industries discharging to the St. Lawrence River.

[2] Agricultural residual is the difference between the amount of N or P available to the growing crop and the amount removed in the harvested crop; data are not available as to the portion of this residual that moves to surface or ground waters.

Discharge of industrial wastewater is another major source of N and P to the environment. Improvements to process technologies during recent years have resulted in reductions in nutrient loading to the environment from certain industrial sectors. However, not all industries are monitored in all provinces or territories, thereby making it impossible to obtain accurate estimates of industrial N and P loading to the environment. There are also no national figures for losses due to leaching from industrial landfills.

Agricultural activities are the largest non-point source of nutrient loading to the environment. In 1996, approximately 55 thousand tonnes of P and 293 thousand tonnes of N remained in the field after crop harvest (Table 1). Although there is no national information on how much of this residual P and N moves to surface or ground waters, a recent assessment of N losses from agricultural land where the soils have a water surplus predicted that 17% of Ontario, 6% of Quebec and 3% of Atlantic farmland would produce runoff or seepage water with >14 mg N/L (Macdonald 2000). In British Columbia, 5% of the agricultural land has a water surplus and 69% of this area was predicted to generate runoff or seepage water with N concentrations >14 mg/L. Given projected increases in intensive livestock operations and crops with high nutrient demands, nutrient losses to surface and ground water as a result of agricultural activities are likely to increase in future.

Aquaculture is a small but growing source of nutrients to Canadian waters (Table 1). Nutrient release from fish production systems results from the excretion of dissolved or solid waste and from unconsumed feed. Although aquacultural losses represent a comparatively small quantity on a national scale, they can be a substantial input to the small bays where aquaculture is typically practiced.

Forest management practices that disrupt the cycle of nutrients between the soil and trees (e.g., timber harvest, site preparation and slashburning, and fertilization) may increase stream water concentrations of N and, to a lesser extent, P. However, because the effects have been studied at relatively few sites in Canada, changes in nutrient loading caused by forest management practices cannot be described for most of the country.

Knowledge and Program Needs

This review has demonstrated the national scope of nutrient-related impacts on aquatic ecosystems in Canada. There is clear evidence that nutrients released to the environment from human activity are impairing the health of certain ecosystems, contributing to quality of life concerns for Canadians and, on occasion, endangering human health.

Although we have documented deleterious changes in Canadian ecosystems as a result of nutrient loading and the impacts of these changes on the quality of life of Canadians, our ability to assess ecosystem change was constrained by data limitations. These limitations could largely be divided into two categories: insufficient knowledge as to the effects of nutrient additions to ecosystem and human health, and insufficient monitoring data of emissions and discharges and ambient conditions.

Insufficient knowledge of the effects of nutrient addition on ecosystem and human health

Nutrient management is a persisting environmental issue unlike others, such as toxic chemicals that can be eliminated by reformulation or discontinuance. Additional research is required to understand the effects of added nutrients on Canadian ecosystems. Areas requiring particular attention are:

- The role of nutrients in inducing blue-green algal blooms and toxin production.
- The role of nutrients in causing taste and odour problems in drinking water supplies.
- Interactions of nutrients with organic contaminants and their effects on aquatic food webs.
- Effects of sewage and industrial wastewater plumes on aquatic life during periods of ice cover (i.e., limited mixing of the plume and cold water temperatures).
- Fate and transport of nutrients within different ecosystems (wetlands, coastal waters, rivers, and lakes) and effects on biota.
- Effects of long term (decades) of nutrient loading on aquatic and terrestrial ecosystems, including water and sediment/soil quality and food webs.
- Effects of forest management practices and agricultural activities on nutrient loss and transport to aquatic ecosystems and groundwater.
- Cumulative effects on the aquatic environment from the combination of several nutrient sources all operating within a region.
- The relationship between nutrient concentrations and aquatic plant biomass, particularly for streams and coastal waters, and the level of aquatic plant biomass that begins to impair beneficial uses of streams.

Insufficient monitoring data

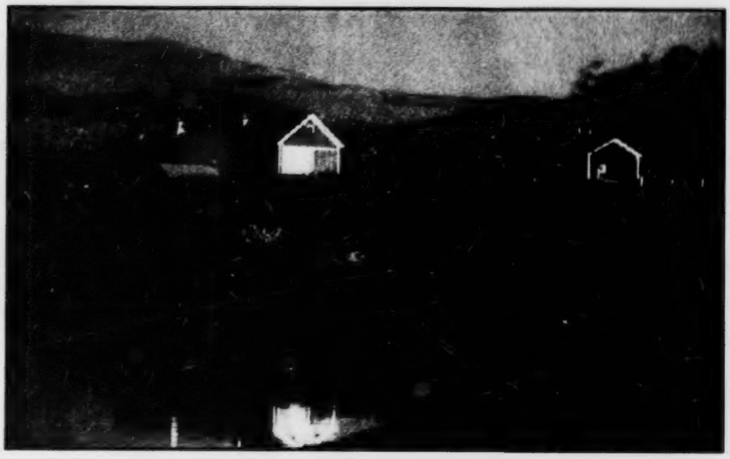
Although every attempt was made to define the status of Canadian ecosystems with respect to nutrients, data on sources and impacts became progressively less available as one moved from lakes to rivers/streams to wetlands to groundwater to coastal waters to forests. Topics requiring particular attention are:

- Industrial loading to surface waters. At present, the availability of N and P data for industries not connected to municipal wastewater treatment plants is erratic: monitoring and reporting requirements vary among provinces and territories, and among industrial sectors. Of the 2130 industries in Canada with discharge permits, we obtained data on nutrient loading for only 91 for nitrate, 142 for ammonium, and 191 for total P. Moreover, the data are not stored in any single database.
- Municipal wastewater treatment plant loading to surface waters. At present, data on N and P loading are available for certain municipal wastewater treatment plants in Canada but the data are not consistent in parameters measured or frequency of sampling. In addition, the data are not stored in any single database. Our analysis of nutrient loading from municipal wastewater treatment plants was achieved by applying per capita nutrient loading coefficients to the population served by the various levels of sewage treatment.
- Agricultural loading to surface and ground waters. Although studies have been conducted at the scale of plots, fields or small watersheds, regional or national estimates of nutrient loading to surface and ground water could not be calculated.
- Atmospheric deposition of P and total N. Although estimates of atmospheric deposition of dissolved inorganic N are available through a network of provincial and federal monitoring sites, data are not available for total N or total P nor are estimates available for release from various sectors.
- Groundwater quality. Water well survey programs are patchy across the country. Some wells are already above or close to guidelines for nitrate. Little information is available on ammonia and P in groundwater.
- Fish kills from accidental spills/discharges of nutrient-related compounds. Currently, reporting is on a voluntary basis.

This review has clearly documented symptoms of environmental degradation from anthropogenic nutrient loading in Canada. However, science-based solutions are available that can assist in further reducing nutrient losses and, in turn, improving environmental quality. New technologies are emerging that can minimize nutrient loading to the environment. Options for reducing nutrient loading are available, particularly from countries with a long history of nutrient problems. A multi-pronged approach is needed to ensure that protection of water quality from the discharge of nutrients and should include:

- Development of watershed management plans for specific watersheds where lakes, rivers or estuaries are already eutrophic due to human activity or are, as yet, undeveloped and sensitive to nutrient enrichment.
- Development of nutrient guidelines for the protection of aquatic life for different types of water bodies (streams, lakes, coastal waters and wetlands) and for different ecoregions in Canada.
- Improved monitoring of industrial, municipal wastewater and agricultural nutrient loading to surface and ground waters.
- The development of nutrient management plans or codes of practices to reduce nutrient loading from specific sectors which have a broad geographic coverage and which in general need better nutrient management (e.g., municipal wastewater treatment plants, industries, agricultural activities, aquaculture operations).
- Research on environmental indicators, technologies to recover and recycle nutrients, management practices (technology-based and environmental) that minimize nutrient losses.
- Expanded public education on the prevention of water contamination by nutrients.

This range of different instruments is needed if we are to counter nutrient impacts on surface and ground waters and give effect to the principles of economic and environmental sustainability.



Available nitrogen and phosphorus have increased dramatically in the past few decades, with widespread environmental consequences.

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7. AQUATIC ACIDIFICATION

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Current Status

"Acid rain" was identified as a potential ecosystem stressor as far back as the 19th century (Smith 1872) and reports by Scandinavian scientists (e.g., Odén 1967) are often credited with bringing the issue to worldwide attention. Nevertheless, Canadian studies have been in the vanguard of defining the aquatic effects of acidic deposition. As far back as the late 1950s, Gorham (1957) and Gorham and Gordon (1960) reported the occurrence of acidic lakes near Halifax, Nova Scotia, and Sudbury, Ontario, but as an environmental issue in Canada, surface water acidification gained real prominence during the 1970s. Beamish and Harvey (1972) observed losses of fish species in the La Cloche Mountain lakes of Ontario that they linked to acidification caused by atmospheric deposition of pollutants presumed to originate from the nearby smelters at Sudbury. Soon after, several studies demonstrated that lake acidification was a regional phenomenon (e.g., Dillon et al. 1978; Watt et al. 1979).

In response to this early work, many research and monitoring projects were initiated by federal and provincial governments, universities and industries to document and/or predict the extent and magnitude of the chemical and biological effects of acidic deposition on Canadian surface waters. An enormous scientific literature subsequently developed, permitting preparation of a sequence of review or assessment reports (i.e., Harvey et al. 1981; Canada-U.S. 1983; RMCC 1986; Schindler 1988; RMCC 1990; Neary et al. 1990; Minns et al. 1992; Jeffries 1997). Parallel concern also developed in the U.S.A. resulting in the National Acid Precipitation Assessment Program (NAPAP) which culminated in a comprehensive scientific review of the issue (Irving 1991) and integrated assessment reports (NAPAP 1991, 1998). Bilateral activities such as those conducted for the Conference of New England Governors and Eastern Canadian Premiers have also generated review documents (e.g., Dupont et al. 2000; Jeffries 2000). Clearly, aquatic acidification is a mature environmental issue in Canada.

The scientific consensus on aquatic effects obtained during the late 1970s and early 1980s played a significant role in justifying SO_2 and NO_x emission controls both in Canada and internationally. In 1979, Canada signed the United Nations Economic Commission for Europe (UN ECE) Convention on Long-Range Transboundary Air Pollution (LRTAP) to reduce and prevent this phenomenon. A domestic "Acid Rain Control Program" was established in 1985 which required a 40% SO_2 emission reduction from 1980 levels by 1994 in the seven easternmost provinces. The commitments of this Program were further codified and extended when Canada entered into a number of international agreements: the UN ECE SO_2 Protocol in 1985, the UN ECE NO_x Protocol in 1988, most importantly the Canada-U.S. Air Quality Agreement (AQA) in 1991 which established national and eastern emission caps and required an approximate 40% SO_2 emission reduction in the U.S.A. as well, and the second UN ECE SO_2 Protocol in 1994. Finally, recognizing that existing levels of acidic deposition are unlikely to promote widespread recovery of aquatic (and terrestrial) ecosystems, a "Canada-Wide Acid Rain Strategy for Post-2000" was signed in 1998 by the federal-provincial-territorial governments which has a long-term goal of reducing acidifying emissions to meet critical loads. The critical loads and emission reductions required to meet them are presently under review and negotiation. In addition, the Strategy calls for periodic assessments, the next being in 2004.

Both Canada and the U.S.A. have significantly reduced SO_2 emissions. Total North American emissions are now ~40% less than in 1980. Canada attained both of its AQA targets by 1993, and in 1997, SO_2 emissions were 18% and 24% below the national and eastern caps respectively. Similarly, US SO_2 emissions are below allowable levels (23% in 1997) and further reductions are expected as Phase II of the US Acid Rain Program is implemented between 2000 and 2010. In contrast, total North American NO_x emissions have changed relatively little.

Over the past 25 years, the nature of aquatic acidification in Canada has been established by: (a) regional surveys of (thousands of) lakes to define chemical and to a lesser extent biological conditions, (b) monitoring at (hundreds) of sites to detect change, (c) research at a relatively small number of sites (<10) to understand the ecosystem processes that control ecosystem change and their limits, and (d) model development and application to spatially extrapolate current and project future conditions. Current work tends to focus both on verifying the effectiveness of existing emission controls and on addressing important knowledge gaps that still remain.

The Canadian area of concern with respect to aquatic acidification is usually restricted to the southeastern part of the country where elevated acidic deposition (pH <5.6) and acid-sensitive terrain are spatially coincident. This area contains approximately 800,000 water bodies. About 1% of these lakes (proportion highest in Ontario) were chemically surveyed in the 1970s and 1980s. Because of a real or potential increase in nearby acidifying emissions, there is now concern for some waters in southern British Columbia and northern Alberta and Saskatchewan.

The waters of Atlantic Canada are generally the most sensitive (i.e., have low base cation concentrations) and exhibit the greatest proportion of acidic systems (alkalinity <0). Lakes in Ontario and Quebec are generally less sensitive with lower acidic proportions relative to lakes sampled in the Atlantic provinces. Lakes in western Canada generally exhibit low sensitivity and almost no evidence of anthropogenic acidification. There are exceptions to these generalizations however, e.g., the extremely sensitive lakes found in the Killarney area of Ontario and in the Côte-Nord region of Quebec. Bedrock and surficial geology is the most important determinant of terrain sensitivity, but climate and other terrain characteristics such as the occurrence of wetlands may be influential as well. Paleoecological analyses almost always show that the onset of lake acidification coincided with the likely time of increased acidic deposition, i.e., early to mid 20th century.

The spatial variation in lake SO_4^{2-} reflects the pattern of SO_4^{2-} deposition with local differences usually related to a within-catchment retention mechanism (e.g., SO_4^{2-} reduction in wetlands). Where in-lake SO_4^{2-} reduction is significant (usually lakes with long water retention times), the associated internal alkalinity generation is an important amelioration to acidic SO_4^{2-} inputs. Sulphate deposition is the primary acidifying agent in Canada. Nitrogen-based acidification is significant in <10% of the lakes for all regions but its importance may be increasing as elevated nitrogen deposition accumulates with time in lake drainage basins. Natural acidification by organic anions (A^-) occurs in all provinces but is particularly important in Nova Scotia, Newfoundland, and eastern Quebec (and perhaps northern Alberta) due to the high terrain sensitivity.

Results of fish surveys and monitoring suggest that pH is the principal factor affecting fish species richness although other factors such as lake morphometry, elevation, and aluminum, calcium and dissolved organic carbon (DOC) concentrations may be influential as well. Reductions in fish abundance and distribution linked to low pH generally occur from impaired reproduction and mortality of early life stages. Studies also confirm that zooplankton species richness is related to lake pH and/or alkalinity, but once again, many other factors such as lake morphometry, nutrient status, and the presence/absence of zooplanktivorous fish also play a role. Acidification causes reductions in macroinvertebrate species richness, particularly losses of calcium-rich taxa that are an important component of the food chain for higher trophic levels. Most effects on water-dependent birds accrue through changes in quality and quantity of foods. Overall, acidic deposition has been ranked as one of the most serious threats to aquatic biodiversity (Biodiversity Science Assessment 1994). An important outcome of this work was specification of a chemical threshold (pH = 6) at or above which most aquatic species are protected from harm.

There are between 100 and 200 lakes in southeastern Canada with sufficiently complete chemical records to permit evaluation of their acidification trends over the last 20 years. The number of lakes has generally decreased over the last decade as some monitoring programs were reduced or discontinued. A statistically significant decline in SO_4^{2-} is the most common chemical trend occurring in about 90% of monitored lakes in Ontario and Quebec (SOE 1999) but only in about half of monitored Atlantic Region lakes. The more prevalent occurrence of significant SO_4^{2-} declines in Ontario and Quebec lakes seems to reflect the greater absolute declines in SO_4^{2-} deposition observed in these provinces. Trends in all other chemical variables were much less consistent both between lakes and between regions. In particular, SOE (1999) reported that about 85% of monitored lakes in Ontario exhibited an improving acidity status (increasing pH or alkalinity), but this result is unlikely to apply to the whole province since the data set available for analysis was heavily weighted with Sudbury-area lakes that have been influenced by substantial SO_2 emission reductions at local smelters. In Quebec, only 27% of monitored lakes showed an improving acidity trend, although there is evidence that lakes near Rouyn-Noranda are just beginning to show improvement related to implementation of local SO_2 controls in 1989. In the Atlantic region, only 13% of monitored lakes had an improving acidity trend and 78% showed no change. Given that present SO_4^{2-} deposition levels still exceed the critical load for most of the monitored lakes, the limited evidence of improving acidity makes sense.

Several biogeochemical processes moderate the rate of lake response to declining SO_4^{2-} deposition, and these no doubt are the reason(s) for the lack or inconsistency in acidity trends. The processes include: (a) depletion and restoration of the soil pool of base cations, (b) temporary storage and release of acid anions in wetlands and/or forest soils, (c) changes in DOC inputs from lakes' drainage basins, and (d) competing stressors related to climatic variation and continuing high levels of nitrogen deposition. Clear lakes appear to respond more directly to reduced acidifying inputs than do coloured lakes, i.e., those having higher levels of natural organic acidity. Studies of experimentally acidified lakes suggest that when lakes are acidified to pH <5, internal alkalinity generating mechanisms may be damaged which will also reduce the recovery rate. Just as it has taken several decades to reach the present state of water acidification in southeastern Canada, it will take several decades before higher pH or alkalinity is the predominating response to reduced acidic deposition.

Biological recovery will lag behind chemical recovery, and hence, it is not surprising there is limited evidence on biological trends. Some of the best information on biological recovery comes from Sudbury-area lakes where studies have documented encouraging biological responses to improving chemical conditions. Phytoplankton and zooplankton species richness has increased as pH increased in Sudbury lakes. The increase was greater for phytoplankton than for zooplankton implying that the former is more resilient. However, richness is still lower than in other lakes of the area that never acidified. There have been few cases of natural recovery of fish communities, but the improved water quality has allowed successful restocking of extirpated fish species. In general, biological recovery at Sudbury is still at an early stage. Outside of Sudbury, there is little evidence of regional recovery of aquatic biota in the remainder of southeastern Canada.

Experimentally induced changes in lake acidity have also provided information on how biological recovery may proceed. Liming a lake near Sudbury that had only acidified to pH 5.7 resulted in complete recovery of the zooplankton community within 10 years; however, liming of strongly acidified (pH 4.5), metal contaminated lakes has not caused recovery of the zooplankton community, even after 15 years. The recovery phase of whole-lake acidification experiments at the Experimental Lakes Area (ELA) corroborate the Sudbury observations. Biological recovery of a lake artificially acidified to a pH of approximately 5.0 did occur to a great extent over a 12-year period, but recovery in a more strongly acidified lake (pH 4.5) has been extremely slow and the community may never return to the original structure.

Trends

Many mathematical models simulating aquatic chemistry and to a lesser extent biology have been developed and used both to predict the response of lakes to changes in acidic deposition and/or their status for given deposition scenarios, and to infer the deposition reduction required to achieve a specified chemical or biological goal. While both steady-state and time-dependent models have been used in Canada, applications of the former are much more prevalent because they are simpler to perform and less demanding in terms of input data. All models use SO_4^{2-} deposition as the primary acidifying driver. To date there are only a few cases where nitrogen deposition has been considered also. Substantial uncertainty is present in the projections made by both steady-state and time-dependent models. Nevertheless, the predictions seem reasonable. A lack of understanding of some of the details of acidification processes is a primary cause of uncertainty, and in particular, most of the biogeochemical processes that are moderating acidification recovery (noted above) are not considered by the models.

For assessment purposes, an Integrated Assessment Model (IAM) has been developed which permits linkage of several sub-models, i.e., a continental-scale atmospheric transport, source-receptor model to estimate SO_4^{2-} deposition for a given SO_2 emission scenario; steady-state water chemistry models to estimate lake alkalinity and pH; fisheries and zooplankton response models; and water bird response models (Lam et al. 1998).

The IAM has been used to estimate steady-state pH of lakes in southeastern Canada for three scenarios of SO_4^{2-} deposition reflecting the situation: (a) before implementation of the SO_2 emission controls required by the AQA, (b) after implementation of Canadian controls, and (c) after implementation of Canadian and U.S.A. controls (Jeffries et al. 2000). Modelled lake pHs were always less than their estimated original values. To assess the ecological significance of the pH reduction, scenario "damage" was quantified as the percentage of lakes having pH <6. Care was taken to account for naturally acidified lakes. The IAM predicted that Canadian SO_2 controls will reduce damage in Ontario and Quebec but have little effect in Atlantic Canada. Implementation of U.S. SO_2 controls will further reduce damage throughout all regions, although it is conservatively estimated that ~76,000 acid-sensitive lakes in southeastern Canada (or ~970,000 ha of lake area) will remain chemically damaged (pH <6) unless additional reductions in SO_2 emissions are implemented beyond those required by the AQA. Linking the lake pH estimates to fish response models suggests that there will be a net loss of ~162,000 fish populations in southeastern Canada (relative to the original condition) when AQA controls are complete.

Critical loads for SO_4^{2-} deposition have been determined by in effect running the IAM backwards, i.e., estimating the deposition that maintains water chemistry over the pH 6 (or similar alkalinity) threshold criterion (Jeffries et al. 1999). For example, critical load values of <6, 6.9, 8.0 and 13.2 kg wet $SO_4^{2-}.ha^{-1}.yr^{-1}$ were determined for lakes in the Kejimkujik region (Nova Scotia), Montmorency region (Quebec), Algoma region (Ontario), and Sudbury region (Ontario), respectively. Wet SO_4^{2-} deposition presently exceeds these critical loads by ~7 to 12 $kg.ha^{-1}.yr^{-1}$. Moreover, it is also expected to exceed them by ~6 to 10 kg wet $SO_4^{2-}.ha^{-1}.yr^{-1}$ even after all SO_2 emission controls required by the AQA are finally implemented. Hindar and Henriksen (1998) also used a steady-state model to determine a critical load of ~14 kg $SO_4^{2-}.ha^{-1}.yr^{-1}$ for Killarney lakes near Sudbury and to estimate that an approximately 50% emission reduction beyond AQA requirements will be needed to eliminate critical load exceedances. However, Hindar et al. (2000) later suggested that strong nitrogen retention may make these lakes less sensitive than originally predicted.

Knowledge and Program Needs

Many knowledge and/or information gaps exist that limit either understanding of the rate, pathway, and endpoint of ecosystem recovery or the ability to assess it:

- Survey information for lake chemistry is very old and essentially useless for assessing current acidity status. New surveys should be conducted to permit such assessments and to directly quantify regional changes from previous conditions. Similarly, existing information on lake biota (e.g., fish and zooplankton) is extremely patchy and new surveys are needed to fill in geographical gaps in the Atlantic provinces, Quebec and northern Ontario.
- Monitoring activities have declined to the point that assessment of change is problematic. While this is true for both chemical and biological monitoring, it is the latter that is in a particularly grave condition. Several biomonitoring pro-

grams have been completely abandoned. Failure to sustain monitoring of isolated species extinctions prevents detection of either continuing species losses or re-invasion. In short, insufficient information is being collected to directly evaluate biological responses to changing deposition levels. Commitment to long-term monitoring programs is needed.

- There is evidence that the cumulative effects of elevated nitrogen deposition may undermine the benefits expected to accrue from SO_2 emission control. Determination of the status of Canadian lakes and their catchments with respect to nitrogen saturation and the controlling factors is necessary and will be a complicated task.
- Acidic deposition has been eroding the base cation pool in Canadian Shield soils for many decades. This acts both to delay water acidification at the beginning and recovery later on. Depletion of base cations, particularly calcium, may also have biological implications for recovering aquatic ecosystems, since some key organisms have relatively high calcium requirements. Moreover, base cation depletion has ecological implications beyond the acidification issue, e.g., reduced forest productivity and carbon sequestration. Information on the status of the soil base cation pool and its replenishment rate by weathering is needed.
- There is evidence that reduced forms of sulphur and nitrogen stored in wetlands, stream beds and stream margins, and in forest soils are being re-oxidized and mobilized under drought conditions. This phenomenon will certainly delay recovery from acidification. Estimates of the size and reactivity of the stored sulphur pool in catchments and the time frame over which it might affect lake recovery are needed.
- Recognition of the importance of DOC in aquatic ecosystems continues to grow as interactions with other ecosystem stressors, influences on biological communities, etc. are identified. More research and monitoring of brown water systems is necessary before their functioning is understood. Conversely, very clear lakes appear to be highly sensitive to the interactive effects of acidification and other stressors including UV-B and warming, requiring studies that address biological effects in a multiple-stressor context (see also point 11 below).
- The expectation that recovery will proceed directly towards the original biological (and perhaps even chemical) state is clearly incorrect in some cases. Whether or not the new biological makeup of such ecosystems is sustainable in the long term has not been demonstrated. Typical, not necessarily original, community structure appears to be a reasonable goal for recovery, however, up-to-date biological surveys of reference lakes are needed to establish what is typical, i.e., appropriate recovery targets (see also point 1 above). The simplified communities that result from acidification may be particularly vulnerable to invasion by exotic species from abroad.
- The regional impact of episodic acidification on aquatic biota remains largely unexplored as does its implications when determining ecosystem critical loads.
- Many diagnostic tools that quantify biological effects have been abandoned for a decade or more, e.g., fish population monitoring using failed reproduction and missing year classes, and in situ assessment of the toxicity of episodes via monitoring plasma and tissue ions and gill aluminum concentrations. As such, our notion of the "current status" of biological effects is very out-of-date.
- There is a general lack of understanding of the processes that affect biological recovery. For example, what is the relative influence of biological versus chemical controls on community recovery, or within-lake versus watershed factors on recolonization or community restructuring?
- To date, most models used to project aquatic responses to acidic deposition (e.g., the IAM) have focused on SO_4^{2-} as the principal acidifier. To satisfy future assessment needs, the models should be modified to include nitrogen-based acidification and to reflect other advances in knowledge as they occur. New observations should be used to post-audit the models if applicable, e.g., confirm the accuracy of earlier projections. Empirical and experimental data on the patterns of biological recovery are needed to improve the linkage between chemical response and biological models. The projections provided by steady-state models give no indication of the time required to achieve them. Dynamic models do provide temporally based projections but require much more input data to calibrate and run them. Wherever such data exist or can be obtained, application of dynamic models is recommended to supplement the steady-state results and place them in a more realistic framework.
- Interactions of acidification with stressors such as climate change (or variability), toxic contaminants (e.g., mercury), UV-B, declining nutrient and/or base cation export from terrestrial catchments, etc., all have major implications for the chemical and biological status and recovery of aquatic ecosystems. Understanding the processes resulting in lake acidification cannot be separated from understanding the processes of terrestrial acidification. Cooperative interdisciplinary research into these interactions is needed. The tendency to "pigeon-hole" issues as a mechanism for simplifying research management often impedes interdisciplinary work.

Aquatic ecosystems are sensitive indicators for effectively assessing the effects of acidic deposition and the changes arising from emission control. It is clear that the Canadian "story" of aquatic acidification is far from complete. Understanding of the acidification process is well developed, but the same is not true for the de-acidification or recovery process. Many uncertainties still require resolution. A vigorous program that integrates chemical and biological monitoring, process research and modelling is needed to meet the assessment expectations voiced in the Canada-Wide Acid Rain Strategy and to ensure protection of an invaluable resource. Current scientific activities are inadequate.

Modelling studies use the current state of knowledge to predict what will happen as the effect of reduced emission of acidifying pollutants is manifested in the chemistry and biology of aquatic ecosystems. The projections give useful guidelines as to the magnitude of reduction needed to achieve a desired environmental goal. Nevertheless, unequivocal verification of ecosystem responses to reduced deposition can only be obtained by suitable monitoring. Monitoring and modelling are mutually supporting assessment activities and both must continue.

Sampling to quantify stream chemistry.

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8. ECOSYSTEM EFFECTS OF GENETICALLY MODIFIED ORGANISMS

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Current Status

In this paper the term genetically modified organism (GMO) is taken to mean an organism that is derived from recombinant DNA technology or genetic engineering, and not derived from classical selection techniques (e.g., breeding plants to create new varieties).

In the new and rapidly growing area of biotechnology, the Federal Government is challenged to manage risks and uncertainties with regard to human health and environmental health. This is manifestly difficult because the knowledge required to make sound societal decisions in fast-moving areas is usually lacking. It is clear that with regard to GMOs and GM foods there is great debate. While the public appears to be more comfortable with medical uses of products of biotechnology, the issue of potential effects of GM foods on human health has caused a furor, originally in Europe and now in North America. There has been, relatively speaking, less public debate about potential ecosystem effects of GMOs. This is a relatively newly recognized issue. A recent influential report prepared by national academies of sciences of several countries (National Academy Press 2000) concluded, among other things, that "concerted, organized efforts must be undertaken to investigate the potential environmental effects—both positive and negative—of GM technologies in their specific applications." Because environmental protection is one of the central mandates of Environment Canada and because there are significant public expectations that the Department will take appropriate actions to ensure that the environment is protected with respect to GMOs, it is important that Environment Canada ensures that the environment is protected by current legislation, regulations, and programs.

In 1983 the Minister of State for Science and Technology introduced the National Biotechnology Strategy, and formed a National Biotechnology Advisory Committee, whose focus initially was on economic aspects of biotechnology, as well as the clarification and development of regulatory capacity and human resources. The *Canadian Environmental Protection Act* of 1988 allowed Environment Canada to regulate products of biotechnology not regulated under other legislation, and gave it the legislative authority to set minimum standards for notice and assessment of all products of biotechnology. The Federal Government's plan for a national regulatory system for human and environmental health aspects of products of biotechnology evolved over the period 1990 to 1995. The intent was to regulate genetically engineered products in the same way as traditional products. For example, for GM agricultural products, the Canadian Food Inspection Agency and Health Canada have legislative responsibilities under the *Seeds Act*, the *Feeds Act*, the *Fertilizers Act*, the *Health of Animals Act*, and the *Food and Drugs Act*. Environment Canada's legal mandate in biotechnology is derived from its responsibility under the *Canadian Environmental Protection Act 1999* and from the *Department of Environment Act*, which provides the Department with general responsibility for environmental management and protection.

Environment Canada sponsored a Workshop on the Potential Ecosystem Effects of Genetically Modified Organisms in Burlington, Ontario, February 28-29, 2000 (Maguire 2000). The purposes of this workshop were (1) to develop a common understanding of the potential risks to ecosystem health of GMOs used in sectors such as agriculture, forestry and fisheries, how the Federal Government's regulatory regime currently assesses environmental risks of GMOs, and current relevant research in other government departments and academia; (2) to identify areas of uncertainty in the environmental risk assessment of GMOs, and areas where Environment Canada could and should be involved; and (3) to contribute to the development of a strategy and action plan for Environment Canada to ensure that the environment is protected from the hazards of GMOs. This paper summarizes the results of that workshop, and recommendations for research and other action.

Knowledge and Program Needs

Most workshop participants felt that Environment Canada should be involved in assessing and monitoring for potential ecosystem effects of GMOs in order to ensure that the environment is adequately protected. In order to do this, it was clear that research capacity needs to be developed (in-house or in collaboration with others) before an adequate monitoring program could be put in place. It was also felt by many that the issue of potential ecosystem effects of GMOs could properly be considered as a biodiversity issue at a broad level, i.e., ecosystem or landscape. Following are the most important issues and knowledge requirements raised at the workshop, and later:

- We need to know the long-term cumulative impacts on biodiversity resulting from the dispersal of GMOs in the environment. This includes direct and indirect non-target impacts. In agriculture or silviculture, large-scale field trials are necessary to find the rarer impacts of GMOs. GMO escape from aquafarming operations may be problematic. (See Muir and Howard 1999 for a discussion of risks to a natural fish population after the release of GM fish; and Devlin 1998 for a discussion of the benefits, limitations and risks of transgenic fish for aquaculture). In every situation, what is an acceptable level of impact on non-target organisms or biodiversity? What is a significant effect? What are good bioindicator species to determine impact? A research program on potential impacts of GMOs must be based on understanding their impacts on ecosystems and biodiversity. A deeper understanding and use of molecular genetics and genomics will be essential to conserving and enhancing biodiversity. In that connection, what baseline data are available on the current status of ecosystems that will allow us to determine the "true" impact of GMOs?

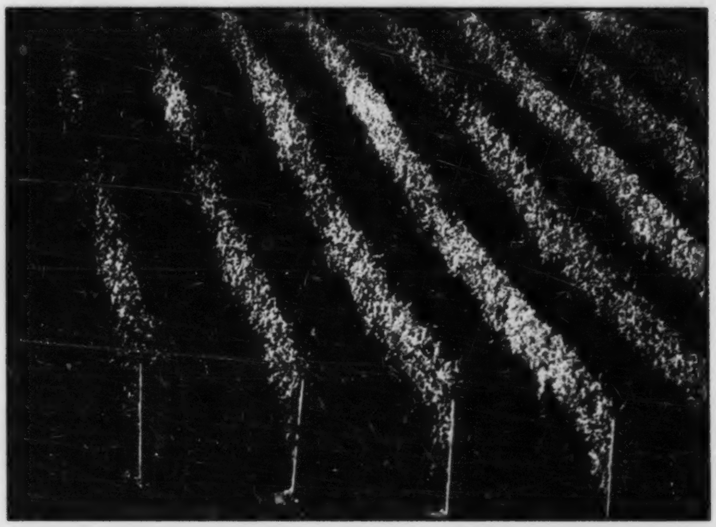
- Other important areas of interest are the uncertainty involved in current environmental risk assessments being conducted by other federal government departments; the quality of data (standardization of test methods, quality assurance/quality control); the desirability of multiyear studies (because year-to-year variation may be large) and multisite studies (because site-to-site variation may be large); and modelling to aid our predictive capacity in extrapolating from the lab or small plot scale to much larger scales. In our research and monitoring we need to use, or develop, the most sensitive diagnostic molecular biological tools.
- We need to know the potential impacts on soil and stream microorganisms and invertebrates (and organisms at higher trophic levels) of engineered insecticidal residues (e.g., *Bacillus thuringiensis* in crops). (See Donegan et al. 1997 for an account of the persistence of some genetically engineered products of tobacco plants in soil, and the U.S. National Research Council 2000 for a review of the science and regulation of genetically modified pest protected plants). Is there a possibility of horizontal gene transfer between GM plants and soil bacteria?
- Possible future developments with GMOs that may be problematic include GMOs with multiply-engineered traits (resulting from "gene stacking"), which may have unpredictable effects on non-target organisms, or which may result in invasive species or "super weeds."
- Might GMOs become reservoirs of diseases, or transfer diseases to indigenous species?
- Might GMO waste management become problematic?

In addition to these issues, it should be recognized that an overall environmental assessment of the risks and benefits of GMOs to ecosystems must at least consider, on the one hand, a comparison of environmental damage of GMOs compared to alternative techniques and, on the other hand, what "collateral" damage might be inflicted through the use of GMOs. An example of the former would be a comparison of total pesticide burden in an ecosystem under two scenarios: the use of a GMO that expresses pesticides, and purely chemical spraying of a non-GM crop. An example of the latter would be a need to harvest more small wild fish to be processed into fishmeal to feed fast-growing GM fish. In addition, if GM aquafarming becomes more intensive in the future, it may exacerbate known problems with non-GM aquafarming such as excess nutrient discharge, and release of antibiotics and pesticides to aquatic environments.

The following are observations and recommendations with respect to Environment Canada's role and science capacity needs:

- If Environment Canada initiated a program of research and monitoring on potential ecosystem effects of GMOs, it would collaborate with other federal government departments (and academia and the private sector) to ensure coordination, minimize duplication and disseminate results. A 5-Natural Resources departments working group would greatly facilitate our expansion into this area. It was strongly felt by Environment Canada workshop participants that the Department should have the capacity to ensure the sufficiency of current regulations on GMO use, from an environmental perspective. Important areas of interest to Environment Canada are the uncertainty involved in current environmental risk assessments being conducted by other federal government departments; the quality of data (standardization of test methods, quality assurance and quality control—see, for example, Vaïtilingom et al. 1999); the desirability of multiyear studies (because year-to-year variations may be large) and multisite studies (because site-to-site variation may be large); and modelling to suggest appropriate sampling programs (see Squire et al. 1999 for a discussion of modelling gene flow at the landscape level).
- An Environment Canada program on potential ecosystem impacts of GMOs must be based on understanding their impacts, if any, on ecosystems and biodiversity. A deeper understanding and use of molecular genetics will be essential to conserving and enhancing biodiversity.
- Environment Canada needs to work with others in developing its research and monitoring plans to ensure that the most sensitive diagnostic molecular biological tools are used, and that there is adequate predictive capacity in extrapolating from the lab or small plot scale to much larger scales.
- Resource issues are considerable, and it is clear that competing priorities will need to be reconciled. Currently, Environment Canada does have ecological and risk assessment experts involved in other areas. It is clear that such expertise will be required in any new program on potential ecosystem effects of GMOs, as well as expertise in molecular biology. Environment Canada also needs expertise on population genetics, on several groups of small organisms (e.g., insects), and landscape ecology, among other fields.
- It is critically important to have effective communication with the Canadian public on the potential ecosystem effects of GMOs. Because there are significant public expectations that Environment Canada will take appropriate actions to ensure that the environment is protected, it is important that the Department develop better lines of communication on ecosystem risk with other federal government departments. It is also important to share relevant information with academia and the private sector, and with provinces and territories and such agencies as the OECD, the EU, the U.K. Department of Environment and the U.S. Environmental Protection Agency.

- It is important to realize that there are many important ethical, legal and social issues involved in the use of GMOs (e.g., the question of society's "right" to transform animals or invent new animals, potential pain and distress in animals used as "production vessels," attempted patenting in the U.S.A. of a cell line developed from human blood, etc.).



Large-scale field trials are needed to determine the impacts of genetically modified organisms in agriculture and silviculture.

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9. MUNICIPAL WASTEWATER EFFLUENTS

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Current Status

Municipal wastewater is a complex mixture of human waste, suspended solids, debris and a variety of chemicals derived from residential, commercial, and industrial sources. It represents the largest source of effluent discharge to Canadian waters, totaling approximately 4300 million cubic metres in 1991 (Statistics Canada 1994). The volume of the wastes, the pollutants they contain, and potential for impacts to water quality make municipal wastewater a concern in Canada.

Historically, sewage treatment was undertaken as a public health measure to prevent the transmission of waterborne diseases. Since the early 1900s, the need to adopt sewage treatment has been recognized for the prevention of negative environmental impacts where municipal wastewater treatment plants (MWTP) effluents are discharged. The identification of the role of phosphorus (P) in causing eutrophication of freshwaters in the 1960s spurred the adoption of P-removal technology at many MWTPs and this was followed in the 1960s to 1980s by adoption of disinfection of municipal effluents to reduce the discharge of pathogens to receiving waters. Traditional wastewater treatment systems are designed to remove settleable solids and floating scums (primary treatment), fine suspended solids and oxygen-consuming material (secondary treatment, lagoons), and nitrogen (N) and/or phosphorus (tertiary treatment). Along with these constituents, MWTPs remove other contaminants including some heavy metals and organic chemicals. These materials come from either human waste or the residential, commercial and industrial products discharged to sewer collection networks. The materials removed from wastewater end up in the organic biosolids or chemical sludges. These may be disposed of in landfills or by incineration. Alternatively high quality biosolids are frequently applied to land as an organic enrichment material.

In 1996, 74% of the Canadian population was serviced by municipal sewers. The remaining 26%, mostly in rural areas, relied on individual septic tanks or private treatment systems. Within the municipal population on sewers, 94% were served by some level of sewage treatment while the remaining 6% discharged raw sewage directly to Canadian waters (Environment Canada 1996).

Trends

Population growth and continued urbanization will continue to increase the quantity of wastewater discharged to MWTPs. Public expectations will increase demand on municipalities to provide greater levels of treatment for wastes, on the premise that improved receiving water quality will benefit human and environmental health. These expectations for wastewater treatment are likely to evolve faster than municipalities are able to respond through infrastructure programs. Additionally, MWTPs were designed to remove solids, oxygen-demanding material and, in some cases N or P but may not adequately remove all constituents identified in wastewater. New technologies are becoming available, but may be very expensive.

Many municipalities face problems related to aging infrastructure. Sewer collection networks deteriorate allowing non-wastewater inflow into sewers, thereby adding to the volume of water that must be treated. MWTPs may not have been expanded to keep up with population growth and may be hydraulically overloaded particularly during wet weather. Significant expenditure may be required simply to maintain existing levels of treatment, let alone meet higher levels of treatment. For municipalities to justify substantial investments in infrastructure renewal or upgrades to higher treatment levels requires an understanding of the environmental implication of these discharges on water quality health and the benefit to be gained by the investment.

Emerging Issues

Some negative effects of municipal wastes have been documented for over a century. Some of these issues remain relevant to this day. New issues continue to become apparent as the science of understanding the environment advances, and the tools and technology of environmental monitoring develop.

Pathogens

MWTP effluent, if not disinfected, contains bacteria and pathogens. Many beaches in urban areas are frequently closed for several days during and immediately after rainfall events because of microbial contamination caused by MWTP overflows, stormwater and CSO discharges. Disinfection of MWTP effluent reduces the risk of microbial pollution although undisinfected discharges still occur. The public health risks of microbial pollution from MWTP effluent to Canadian recreational waters is not well understood. Shellfish harvesting may be restricted due to bacterial contamination from municipal effluent, stormwater, agricultural waste, or leakage from septic systems. In 1992, approximately 3018 km^2 were closed to harvesting due to bacterial contamination along the three Canadian coasts (Chambers et al. 1997). Isolated incidences of microbial contamination of drinking source water in Canada from CSOs, stormwater and inadequately treated MWTP effluent have been reported. Because municipalities treat and disinfect water used for drinking, outbreaks of waterborne disease are rare in Canada (Health Canada 1995a,b).

Oxygen Depletion

Discharge of MWTP effluent with high BOD loads can cause reductions in dissolved oxygen (DO) in the receiving water. DO threats to fish and other organisms often occur during summer months. However, in colder climates where rivers and lakes are ice-covered for many months, DO depletion can occur due to ice cover preventing re-aeration. Acute effects of low DO are normally avoided in Canada as a result of municipal licensing conditions, though little information is available on the effects of chronic DO stress on aquatic organisms, particularly when other stressors are also present.

Toxicity of Effluents

The toxicity of municipal effluents is dependent on a variety of factors, including the size and characteristics of the sewershed, the type and efficiency of treatment and disinfection processes and the physical, chemical and biological characteristics of the receiving waters. In many cases the acute toxicity of MWTP effluent is due to un-ionized ammonia or, in the case of chlorinated effluents, to total residual chlorine. Other contaminants including cyanide, sulfides, phenols, surfactants and heavy metals, such as copper, zinc and chromium, also contribute to acute or chronic toxicity (Chambers et al. 1997). Many factors can moderate the toxicity in the effluent or receiving environment including pH, hardness, dissolved organic carbon and temperature. Despite considerable investment in treatment systems, acute and chronic toxicity remains a concern in many sites receiving municipal effluents.

Many chemicals detected in municipal effluents are hydrophobic and may tend to adsorb to particles in the effluent or sediments in the receiving environment, rather than remain in the water phase. The distribution of these chemicals may therefore differ considerably from more soluble compounds which will tend to move with the effluent plume. Hydrophobic chemicals may also tend to bioaccumulate in organisms and move through food webs. The distribution and fate of contaminants in the environment is extremely complex and dependent on the physical and chemical characteristics of the chemicals as well as the physical, chemical and biological characteristics of the receiving environment.

Under the *Canadian Environmental Protection Act* a number of Priority Substances were identified (PSL-1,2) and risk assessments conducted to evaluate their potential to cause harm in the Canadian environment. Municipal effluents have been identified as major sources of many of these chemicals, some of which have been declared "CEPA toxic." Chlorinated wastewater effluents on the PSL-1 were declared CEPA toxic. Four substances on PSL-2 (ammonia, chloramines, nonylphenol and its ethoxylates and textile mill effluents) are associated with municipal effluents and have been proposed to be declared CEPA toxic. Considerable information on their distribution, treatability, fate and effects are needed in order to develop and implement appropriate risk management strategies.

Eutrophication of Receiving Waters

MWTP effluents contribute nutrients, primarily N and P, to receiving water bodies and thus may cause eutrophication. Nutrients can accrue in the bottom sediments and be released into the water at a later time, and thus have a long-lasting impact on water quality. Nutrient addition to aquatic ecosystems can increase growth of primary producers (algae and rooted aquatic plants) to levels that result in impairment of the ecosystem (e.g., changes in food web structure, changes in habitat, loss of species, infestations of nuisance species). These ecological changes can affect human use of aquatic resources (including water-based recreational activities and fisheries) and impair water quality for municipal, industrial and agricultural users. With the recognition of the role nutrients play in eutrophication, many MWTPs discharging to inland waters have upgraded to reduce P loading. Nevertheless, eutrophication continues to be a pervasive problem due to slow response time of ecological systems to reductions in loadings and uncertainties in establishing ecologically appropriate loading limits.

Biosolids/Sludges

MWTPs generate sludge as a result of decomposition and settling of wastewater as it undergoes treatment (Warman 1997). Biosolids are the organic portion of the sewage sludge that has been stabilized through digestion to meet suitable criteria for application to land (Webber and Bates 1997). Biosolids are rich in inorganic and organic materials and plant nutrients and are therefore a desirable additive to agricultural land. Most provinces have guidelines for the management of land application of biosolids designed to match biosolid nutrient content with the nutrient demands of the crop, while limiting accumulation of heavy metals and potentially toxic constituents. MWTPs generate significant quantities of sewage sludge; the City of Toronto sewage sludge production for 1999 was about 70,000 tonnes dry weight. In Canada, sewage sludge is incinerated, landfilled, or applied to land. Land application of biosolids is expected to increase in the future.

Intermittent Discharges

Discharges from stormwater and combined sewer systems are intermittent in nature, occurring during rain events, and often for brief periods of time. Similarly, wastewater treatment systems, while releasing a continuous discharge of treated effluent, during wet weather may release untreated wastewater (MWTP bypasses) or poorly treated wastewater (reduction of treatment efficiency). Limited information exists to evaluate the effects of intermittent discharges of untreated effluents on water quality, and the ecological significance of these discharges. There is laboratory evidence that short-term exposure to some contaminants may have ecological relevance. Translating this understanding to in situ conditions needs development.

By-products of Treatment

The physical and chemical processes of wastewater treatment may transform wastewater constituents. For example: (i) secondary treatment with activated sludge processes may increase ammonia concentrations in final effluent by converting organic material into ammonia nitrogen; (ii) nitrification to reduce ammonia levels will result in increased nitrate and nitrite levels in the effluent; (iii) degradation of certain components may result in different forms which are not necessarily less toxic (nonylphenol poly ethoxylates degrade to 4-nonphenol, a more toxic material); and (iv) disinfection of effluents with chlorine which results in residual chlorine which is toxic to fish.

Endocrine Disrupting Substances

Municipal effluents are a source of chemicals that may alter endocrine function, thereby adversely affecting reproduction or development in animals (Jobling and Sumpter 1993; Ternes et al. 1999). Natural and synthetic hormones and certain industrial chemicals capable of estrogenic effects have been identified in sewage effluents. These chemicals have been causally linked to changes in reproductive endocrine function in laboratory tests on fish. The extent to which these will have adverse effects on aquatic species or humans is not fully understood. Evidence suggests that these effects may occur even at low concentrations and/or from transient exposure.

Pharmaceuticals and Personal Care Products

Pharmaceuticals and personal care products (such as antibiotics, blood lipid regulators, analgesics, anti-inflammatory drugs, and beta-blockers, fragrances [musks], skin care products, disinfectants and antiseptics) have been detected in municipal effluents and associated surface waters (Daughton and Ternes 1999). Traditionally, drugs were not viewed as environmental pollutants but their potential to cause a variety of physiological responses raises concerns for effects on organisms in the aquatic environment. The array of pharmaceuticals in use will continue to diversify and grow with an aging population and rapid developments in the pharmaceutical industry. We have limited knowledge of the environmental transformation, fate or effects of these compounds. The implications of exposure to these complex mixtures remains unknown.

Pollution Prevention and Treatment Processes

Many industry sectors have embraced pollution prevention to address traditional "end-of-pipe" discharge issues. Understanding the complete picture of a plant or system operation allows innovative ideas for cost cutting, waste reduction, and energy and resource efficiencies to be developed. Increasing demand on water will result in a variety of water conservation measures which will have implications for wastewater management. These efforts are made more difficult for MWTPs due to the complex nature of municipal wastewater. Large municipalities are able to dramatically reduce discharges of undesirable materials through source control, industry education, and municipal infrastructure modifications (e.g., inflow/infiltration control). These can achieve substantial benefits in terms of reduced discharge loading and MWTP bypassing without upgrading treatment facilities. Smaller municipalities may have limited resources that they can devote to these efforts. Facilitation and information sharing of these opportunities is key to reducing wastewater contaminants at source, rather than at the treatment plant.

Ecological Risk Assessment

MWTP effluents have traditionally been regulated based on "specified level of technology" or "end-of-pipe" effluent quality criteria. This form of permitting neither guarantees environmental protection nor assures compliance with all environmental regulation. Ecological Risk Assessment (ERA) is an approach to managing municipal liquid wastes which addresses the site-specific constraints of different receiving environments. However, ERA frequently requires extensive environmental information and interpretation skills not routinely possessed by municipal waste collection and treatment operators. Guidance and development of environmental tools and a regulatory framework for municipalities to conduct ecological risk assessment is needed. Development of these tools and framework could draw from the combined experiences of other industry sectors. This approach would have to ensure that recommendations are based on unambiguous science and provide regulatory clarity for municipalities.

Knowledge and Program Needs

Many of the existing and emerging issues require further development on a policy and regulatory level. However, substantial uncertainties on the sources and treatment and environmental fate and effects still exist and require knowledge and understanding of:

Sources and Treatment

- Improved strategies for control of un-ionized ammonia and other acutely toxic chemicals in sewer systems and MWTPs.
- Sources and understanding of the fate of priority and toxic substances in treatment systems.
- Sources, distribution and fate of environmental estrogens, pharmaceuticals and personal care products in municipal treatment systems.
- Pollution prevention strategies as a complimentary approach to wastewater treatment.
- Waste treatment and disposal quality criteria, objectives and standards based on the environmental and assimilative capacity of the receiving water.

Environmental Fate and Effects

- Sub-lethal effects of dissolved oxygen depletion on aquatic organisms and its contribution to cumulative stress.
- The role of municipal waste effluents and septic system discharges in causing bacterial contamination of shellfish beds and recreational waters.

- Sources, fate and effects of toxic priority substances (e.g., PSL-1,2) in receiving environments.
- The potential impact on groundwater and surface waters of agricultural application of biosolids.
- The role of MWTPs in causing eutrophication and the occurrence of nuisance and toxic algal blooms.
- The ecosystem consequences of by-products of treatment such as residual chlorine, ammonia and metabolites or organic contaminants.
- The relevance of regulatory bioassays to ecosystem integrity.
- The distribution, fate and effects of endocrine disrupting substances on the growth, reproduction and development of aquatic biota in the environment exposed to municipal effluents.
- The potential interactive effects of low-level exposure to complex mixtures of biologically active compounds.
- The implications of potential transfer of antibiotic resistance to the environment.
- Acute and chronic toxicity, bioaccumulation, and biomagnification of contaminants in intermittent discharges.
- The current and long-term trends in water quality associated with MWTP effluents.
- Indicators of ecological effects to assess the potential impacts of municipal wastewater effluents.

Treatment facilities will continue to play an important role in managing municipal wastewater. Continued research is required to ensure that new knowledge and technologies are incorporated into municipal wastewater management and environmental assessments. Beyond end-of-pipe controls, other solutions such as water conservation, infrastructure renewal, or pollution prevention, need to be encouraged. The following actions are recommended to ensure the protection of water quality from the discharge of municipal wastewater effluents into the Canadian environment.

- Encourage infrastructure planning, including technological advances, to ensure that improved treatment and environmental protection measures are not diminished by development or population growth.
- Foster partnering opportunities with federal, provincial and municipal governments for monitoring programs and ecological impact assessments.
- Incorporate municipal wastewater planning with integrated watershed management to account for the cumulative effects of numerous environmental stressors.
- Develop tools and indicators for assessment of environmental impacts of MWTP effluent and a framework for ecological risk assessment.
- Develop and adopt pollution prevention approaches to municipal wastewater planning to minimize influent loadings of undesirable substances.

Municipal wastewater effluents are composed of suspended solids, human waste, debris and chemicals from residential, industrial and commercial sources.

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10. INDUSTRIAL POINT SOURCE DISCHARGES

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Current Status

The mining, petrochemical and pulp and paper industries are of importance to the Canadian economy. Combined, there are over 1200 industrial sites whose productivity represents approximately 10% of Canada's GDP (www.ccpa.org; www.mining.ca; www.paprican.ca). In addition, these industries directly employ more than one million people. Despite this socioeconomic importance, effluent discharges from industrial point sources represent a significant threat to water quality with implications to human health and aquatic ecosystem integrity. Industrial waste discharges can affect ecosystem health through direct and indirect toxic insult, nutrient enrichment, and physical habitat alteration, leading to changes in ecosystem structure and function and overall aquatic biodiversity (Northern River Basins Study 1996). Human health can also be affected via consumption of contaminated fish, shellfish and drinking water, or via physical contact in recreational and occupational pursuits (Armstrong et al. 1995; Muir and Pastershank 1996; Raymond et al. 1999).

The objectives of this document are to identify current and emerging threats of the pulp and paper, mining and petrochemical industries to Canadian water quality, with emphasis on drinking water and aquatic ecosystem integrity. Expert recommendations are provided for addressing deficiencies in impact assessment and current environmental protection legislation. In addition to examining the contribution of each industry to water quality degradation, we emphasize the important and immediate requirement for cumulative impact assessment and integrated watershed management.

Pulp and Paper Industry

In 2000, the Canadian pulp and paper industry consisted of approximately 125 pulp and paper mills widely distributed across Canada (Langlois et al. 1997). The pulp and paper process produces large volumes of waste effluent, with a typical mill (700 tonne/d capacity) generating approximately 90 to 130 million liters per day (Walden 1976). Effluent, consisting of complex mixtures of hundreds of compounds, many of which remain unidentified, is discharged to a variety of habitats including lakes, rivers, estuaries and coastal environments. The main effects include chronic toxicity to aquatic organisms and eutrophication (Culp et al. 2000; Dubé and Munkittrick 2001; Dubé et al. 2001).

Historically, the environmental effects of pulp and paper effluents can be categorized in three stages. From the 1950s to the late 1970s, discharge of effluents high in fibre and biodegradable organic compounds resulted in significant habitat degradation and acute lethality to resident biota (McLeay and Associates 1987; Folke 1996). In response to these effects, government established "end-of-pipe" effluent quality limits for the fibre concentration in effluents and limits for acute lethality. In the 1970s and early 1980s, we recognized that the effects of pulp and paper effluents were associated with chemical toxicity primarily due to resin and fatty acids, chlorinated phenolics as well as bioaccumulation of chlorinated organics (e.g., dioxins and furans) (Owens 1996). This led to regulations restricting the discharge of these compounds. During the 1980s and 1990s, process modifications largely focused on changing the type and/or volume of bleaching chemicals (substitution of elemental chlorine with chlorine dioxide), thereby reducing the formation and discharge of chlorinated organic compounds, and installing secondary effluent treatment systems. The 1990s was also a period when concern over the impact of pulp and paper effluent largely changed from lethal to sublethal effects, such as reduced growth and reproduction, physiological impairment and endocrine disruption of aquatic biota (Folke 1996). Despite decades of investments to improve the environmental performance of the pulp and paper industry, significant effects on aquatic ecosystem health continue to be documented across the country (Munkittrick et al. 2001).

Mining Industry

There are approximately 900 mining sites across Canada where base metals, gold, potash, coal, and iron ore have been or are being extracted (AETE 1995). Although many of these sites are presently closed or abandoned, the number of operating mines in Canada ranges between 100 and 170. Most facilities are adjacent to freshwater systems in remote areas away from other industrial and urban developments. Most wastewaters are discharged into small, headwater streams where the effluent dominates the flow of the system. Pollution control systems are complicated by diffuse drainage from waste rock piles and tailings areas. In many situations, these surface water streams can have an elevated background level of contamination from the mineralized area, as well as effluents and runoff associated with neighbouring mining facilities. Unlike most other industries, when mines have been closed and abandoned, they still continue to contribute contaminants to local surface waters. In addition, the ownership of these properties is often unknown or non-existent.

Mining effects are much more long-lasting than those from pulp and paper operations; forests regrow and effluents disperse, but tailings ponds and slag heaps persist and continue to exert effects for hundreds of years. The nature of most of the contaminants is also different; metals released from mines do not degrade but remain permanently in the environment. The historical concerns associated with mines included effluent toxicity, discharge of metals, acid mine drainage, siltation, habitat destruction, and stack emissions. Government regulatory initiatives and mitigative actions by the industry have reduced or eliminated these threats at active facilities. Present day concerns from active mines include the longer term effects of chronic exposure to low levels of metals, bioaccumulation, sediment contamination, endocrine disruption, the stability of tailings dams, and the long-term changes to characteristics of surface waters receiving mining discharges. Abandoned mining sites require increased attention to more accurately assess aquatic impacts and to initiate corrective actions.

Multiple mines often exist on the same ore bodies and thus discharge waste waters into the same watershed. This confounds our ability to attribute environmental impacts to specific facilities, and can be further complicated by the natural elevations of metals that can occur in mineralized areas and the contribution of non-point sources of metals associated with the mining operations. Mining regulations deal with industries individually and do not take into account potential cumulative effects. A basin-wide environmental management strategy would provide a more integrated level of protection.

Petrochemical Industry

The petrochemical industry can largely be broken down into three categories: extraction, refining and transportation. These activities contribute $30 billion to the Canadian GDP (4%) and employ approximately 400,000 people at over 200 locations across the country. Petrochemicals are extracted by oil and gas drilling and by oil sands mining. The petrochemical facilities in operation use pollution prevention and remediation strategies that minimize acute environmental effects. This industry is unique among the natural resource sector in that there are few direct effluent discharges into the aquatic environment with the exception of oil sands. For oil sands the threats to water quality are primarily linked to spills, waste product disposal, and long-term reclamation.

Onshore drilling is concentrated primarily in grassland/rangeland regions of western Canada and in southwestern Ontario. Offshore drilling is restricted to the Atlantic coast, although there is potential for development in the western Arctic. Onshore drilling activities generally create minimal direct disturbance to aquatic resources, but they contribute chemicals (hydrocarbons, trace elements, sulphur compounds) to the atmosphere. Chemical deposition influences surrounding low-order water bodies (wetlands, ponds). Continued economic growth in North America accompanied by greater demand for energy will lead to increasing exploration for petrochemical resources. Offshore oil extraction is a growing industry, with potential to influence marine ecosystems primarily through spills. Assessment of offshore issues is beyond the scope of this report.

Bulk carriers transport raw petrochemicals from offshore and through a nationally distributed network of pipelines. Spills have been and will continue to be a significant environmental threat to both marine systems and fresh surface waters, especially as facilities age. Better-constructed pipelines and the use of double-hulled tankers have reduced the potential for oil spills.

Economics and commerce dictate the location of petrochemical refineries and associated industries. They are located on major transportation routes and on water bodies that can provide cooling water (e.g., Great Lakes connecting channels, Lower Fraser River, Saskatchewan rivers, and the Atlantic coast). Refinery impacts on local water bodies result from both raw and waste material processing, chemicals, and industrial waste products. Many petrochemical by-products are hydrophobic and persistent. Consequently, old refineries, processing/storage sites and adjacent water bodies often contain highly contaminated sediment. Sediment contamination at old petrochemical refining sites and abandoned wood-preservation (creosote) plants is a significant concern. PAH-contaminated sediments have been linked to carcinogenic and other effects in resident biota. Subsurface seepage from on-site storage facilities (deep wells, pits) is a potential source of groundwater contamination and of transport to surface waters.

Oil sands occur in the boreal/parkland region of northeastern Alberta. Experimental facilities began operation in the late 1970s. Recent improvements in extraction technology have made oil production from oil sands economically attractive, and have stimulated dramatic expansion in development. Current production is on the order of 250,000 barrels per day. Investment of over $4 billion by the oil industry is expected to triple production over the next 20 years.

Mining requires extensive land clearing accompanied by diversion of local drainage patterns and receiving waters around lease areas. Oil sands extraction and processing uses significant amounts of water, despite efficient recycling technology. Oil sands process waters (OSPW) contain salts, trace metals, PAHs, and naphthenic acids—constituents that are naturally present in low concentrations in local surface waters. Initial acute toxicity to aquatic biota rapidly decreases through time. Bioavailability of persistent compounds accumulated in biota is reduced by complex interactions among the classes of chemicals. All OSPW are stored on site and are isolated from the surrounding ecosystem. Reclamation and restoration plans of mined areas include development of novel dewatering and detoxification structures, including constructed wetlands and lakes. The long-term implications for the aquatic communities developing in OSPW-receiving areas are not completely known, but saline-condition ecosystems are expected to develop as these areas mature.

Trends

Pulp and Paper Industry

The number of pulp and paper effluent discharges has remained relatively constant in Canada over the past 25 years. Although pulp and paper production is estimated to marginally increase in concordance with pulp prices and market demand, the volume of effluent discharged is expected to decrease with industry efforts to reduce water consumption. With the trend toward reduction in water use by mills, effluent will become more concentrated resulting in the potential for exceedance of toxicity-based, end-of-pipe legislation. Therefore, under current legislation, mills will have little incentive to reduce water consumption because increased toxicity will result in non-compliance. An additional projection by the Canadian Pulp and Paper Association suggests that the industry will continue to move towards pollution prevention rather than effluent treatment (www.cppa.org; www.paprican.ca). This is necessitated by the observation that despite mill modernization and installation of secondary effluent treatment at 99% of the mills in Canada, 65% of the mills in 2000 report effects on benthic invertebrates and 80% report effects on fish (Lowell et al. unpublished; Munkittrick et al. 2001). The Canadian EEM program will continue to be instrumental in obtaining the necessary ecological monitoring data to assess the current state of pulp and paper effects on water quality.

Mining Industry

Government regulations concerning metal mines have recently been evaluated and revised through a 7-year process. The process included AQUAMIN, a multi-stakeholder review of the impacts of mining on the aquatic environment (www.ec.gc.ca) conducted from 1993 to 1996 (AQUAMIN 1996). The review concluded that mining effluents had demonstrated impacts on water quality, sediment quality, and on fish and benthic invertebrate communities. The review made a list of recommendations including that the Metal Mining Liquid Effluent Regulation (MMLER) should be amended to include all mines in Canada; to apply more stringent discharge limits; and to require all mines to implement an Environmental Effects Monitoring program (EEM). From 1995 to 1999, The Mining Association of Canada and the federal government sponsored the Aquatic Effects Technology Evaluation (AETE) program, a multi-stakeholder review of environmental techniques and approaches for evaluating the impacts of metal mining (www.nrcan.gc.ca/mets/aete). This program described cost-effective, sensitive tools that could be used to monitor effects in the aquatic environment. Environment Canada initiated a multi-stakeholder process to amend the MMLER based on the recommendations of AQUAMIN, including a metal mining Environmental Effects Monitoring program. The amended regulations were published in *Canada Gazette*, Part I on Saturday July 28, 2001 (www.canada.gc.ca/gazette/).

Petrochemical Industry

Within the rapidly expanding oil sands mining industry, the key constituents of concern are hydrocarbons (PAHs, naphthenic acids), trace metals, and salinity. Of these, chronic toxicity has been most strongly associated with salinity and naphthenic acids. Interactions of these compounds with environmental processes (microbial degradation, UV processes, etc.) are key gaps in our understanding of remediation and biological community development.

The composition of deposited aerial-borne hydrocarbons and associated trace metals resulting from gas-flaring and from volatilization from storage ponds, is poorly known. Although primarily recognized as an atmospheric threat, accumulation in surface waters is possible. The teratogenic, genotoxic, immunotoxic, and bioaccumulative potential of these materials should be examined.

Emerging Issues

Pulp and Paper Industry

- Inconsistency of toxicity-based, end-of-pipe legislation with industry trend to reduce water consumption will require increased emphasis on ecologically based assessment criteria.
- Lack of understanding of the ecological consequences of existing impacts (e.g., the relevance of the discharge of endocrine disrupting substances to aquatic biodiversity are unknown).
- Ecological impacts continue to be documented although the in-mill source and chemical identity of the causative agents remains unidentified. Improved understanding of these chemicals is required as well as evaluation of the feasibility of novel treatment technologies.
- The trend toward reducing the use of chlorine-based bleaching compounds using alternative technologies (e.g., hydrogen peroxide bleaching agents) presents unknown implications on effluent quality and environmental effects.
- The implications of mill discharges to drinking water quality are largely unknown. However, cases of degraded aesthetic characteristics (i.e., colour, odour, taste) have been reported up to 900 km downstream of pulp mills (Armstrong et al. 1995). In addition, the production of chlorate in chlorine dioxide substitution mills can be a human health concern if found in drinking water. Drinking water endpoints are not currently examined under pulp and paper assessment programs.
- Cycle 2 EEM reports suggest that understanding the effects of mill effluents was confounded by other effluent sources and natural variation in as many as 70% of the studies. Many mills are located on large rivers and estuaries near multiple point source discharges (i.e., municipal sewage) making it difficult to attribute effects to a specific mill or source. Therefore, new tools and frameworks for assessing the cumulative impacts of multiple point source discharges are required.
- Understanding cumulative effects necessitates development of regional and national data management programs.

Mining Industry

- Mining technology and the threats to the aquatic ecosystem from mining are not expected to change dramatically in the near future, but new mineral developments are anticipated particularly in remote, pristine, sensitive environments. Future developments are likely to include:
  - expansion of mining activities in the Arctic, particularly related to diamonds;

  - the development of new large mineral deposits such as the potential operations at Voisey's Bay; and
  - continued development and expansion of the oil sands operations in Alberta.
- Abandoned mines will continue to pose a threat to water quality as a result of acid mine drainage and the potential failure of tailings dams. Some of these sites have a predicted acid-generating capacity that will last for centuries.
- Changes in precipitation patterns associated with global warming could increase the risk associated with contamination from aging, abandoned tailings dams.

Petrochemical Industry

- The cumulative effects of rapid oil sands development and onshore drilling within confined geographic regions are unknown. Although individual projects are monitored for environmental risk, the regional consequences of the combined effect of these activities are not clear. In the oil sands mining region, the regional implications of altered ecosystem structure and function accompanying restoration require study and evaluation.
- In order to monitor both chronic effects of point sources and regional-scale background changes, implementation of an ongoing monitoring program analogous to EEM is recommended. The proposed Regional Area Monitoring Program for northeastern Alberta may largely serve this function.
- Reclamation and remediation strategies are integral to the oil sands regional ecological restoration plans. We must know the successional rates and trajectories of constructed and remediated aquatic habitats. There is a complementary need to develop benchmarks and endpoints indicating attainment of ecologically relevant endpoints.
- Oil/natural gas exploration and potential development in the Arctic will be a threat to surface water issues. Northern ecosystems are more vulnerable to degradation than temperate regions because lower temperatures result in slower biodegradation and recovery processes, meaning longer persistence of toxic compounds and disturbance effects.
- Existing petrochemical production and transport facilities in Canada are aging, increasing the potential for spills as a consequence of material failure.

Knowledge and Program Needs

Needs for effects assessment to:

- Identify priority contaminants and mixtures for industrial discharges (i.e., EDS) and treatment alternatives.
- Establish effect thresholds to determine the ecological significance of industrial effects and the significance of mitigation and reclamation efforts; distinguish natural effects from industry-related effects.
- Improve our understanding of the pathways of contaminant action.
- Improve assessment capabilities for sensitive environments (e.g., Arctic ecosystems, estuaries).
- Improve our assessment of active and abandoned industrial sites (e.g., abandoned mines).
- Assess the implications of global climate change on existing industrial infrastructure (e.g., tailings dams) and for the capacity of effluent dilution.
- Assess the effects of aerial emissions on water quality and drinking water quality.

Needs for cumulative effects assessment to:

- Improve our ability to detect industry-specific contributions within confounded receiving environments exposed to multiple effluents.
- Use and enhance our regional and national information management systems to improve our ability to assess, react and predict.
- Include drinking water endpoints in ecological assessments of water quality.

Needs for policy development to:

- Improve and expand EEM programs for industrial sectors.
- Develop cumulative effects assessment approaches that emphasize integrated watershed management.
- Improve incorporation of ecologically based assessment criteria into environmental management strategies to complement existing legislation (e.g., EEM, end-of-pipe regulations).

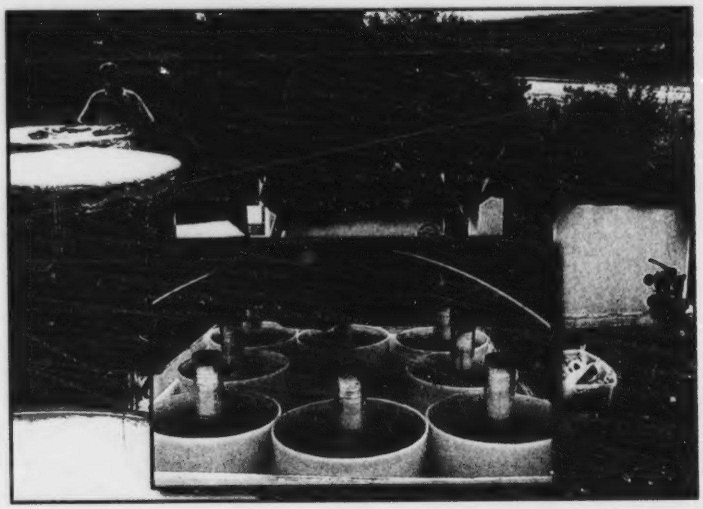
The discharge of industrial effluents into Canadian receiving waters will continue and likely expand with population growth and increased exploration of natural resources. Continued research is required to accurately assess the impact of these industrial effluents on both drinking water supplies and aquatic ecosystem health. Ecosystem or watershed management, which goes beyond end-of-pipe regulation, is required to ensure sustainable development and protection of our raw water supplies. In addition, an integrated approach to management of industrial discharges beyond site-specific assessments is required for assessment and management of the cumulative effects of multiple effluent discharges.

The following actions are recommended to ensure the protection of water quality from the discharge of industrial effluents into the Canadian environment:

- Improve ecological effects assessment by:
  - developing tools, techniques and facilities (e.g., establishment of regional mesocosm infrastructures) for measuring the contribution of industrial effluents to degraded water quality. This includes establishing new experimental facilities at government-university centres of excellence (e.g., NWRI-university facilities);
  - establishing indicators of aquatic ecosystem health; and
  - establishing watershed-based effect thresholds for adaptive ecosystem management.
- Encourage development of assessment programs for sensitive ecosystems and for abandoned industrial sites.
- Encourage pollution prevention and development of novel technologies for reducing the impact of industrial effluents on water quality.
- Develop a national information management system and cumulative effects assessment framework where the effects

of industrial discharges are assessed in conjunction with other point and non-point source stressors affecting water quality. Inclusion of drinking water endpoints into assessment programs and information management systems is critical to ensure our raw water resources are protected relative to their need for human consumption and use.

- Develop policy where federally legislated Environmental Effects Monitoring programs are required across industrial sectors. Policy development is also required to incorporate ecologically based assessment criteria into environmental management strategies to complement existing end-of-pipe legislation.
- Foster linkages between different EC Branches (e.g., EA Branch and AEIRB) and between different levels of government to improve and coordinate data acquisition and information management.



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11. URBAN RUNOFF

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Current Status

Rainfall and snowmelt in urban areas are converted into urban runoff, which is transported by sewers, drainage channels and streams, and ultimately discharged to receiving waters as urban stormwater in areas serviced by storm sewers or as combined sewer overflows (CSOs) in older areas with combined sewers. During transport, the runoff quality is degraded by various pollutants, materials and thermal energy from the urban environment. CSOs represent a mixture of stormwater, raw municipal sewage and scoured sewer sludge, and their composition is comparable to that of untreated sewage. The pollution of both stormwater and CSOs greatly varies during and between rainfall events, ranging from severe (usually during early phases of runoff, also referred to as the first flush) to low, towards the end of runoff events (Marsalek et al. 1993).

Urban runoff has been recognized as a significant environmental detriment during the past 30 years. Both stormwater and CSO discharges cause physical, chemical, biological and combined effects on receiving waters, either of acute or cumulative nature (Harremoes 1988), and seriously impair beneficial water uses in many locations (House et al. 1993).

In new urban developments, some mitigation of flooding and erosion impacts has been achieved by stormwater management practiced during the past 25 years, and some improvements in water quality have been achieved by stormwater quality enhancement practices over the past decade. However, the long-term performance of stormwater management facilities is uncertain. In older areas, requiring retrofit, hardly any progress has been made. Most Canadian municipalities with combined sewers pursue CSO abatement programs, but progress is relatively slow because of high costs (Chambers et al. 1997).

Almost 80% of Canadians live in urban areas (about 25 million in 2001; Statistics Canada 2000). The process of urbanization and associated activities increase runoff flows and degrade runoff quality. In terms of discharge volume and solids load, urban runoff significantly exceeds those associated with municipal wastewater (Chambers et al. 1997). Just in the Canadian Great Lakes region, urban runoff discharges annually in the order of 10^5 tonnes of suspended solids, 10^4 tonnes of chloride, 10^3 tonnes of oil and grease, and 10^2 to 10^3 tonnes of trace metals (Marsalek and Schroeter 1989). Concerns about CSO pollution are similar, with most significant pollutants being pathogens (typically assessed by indicator organisms), solids, oxygen-demanding substances, nutrients and chemicals from small industrial and commercial sources.

The evidence of serious impacts of these discharges was found in one half of the Areas of Concern in the Canadian Great Lakes region, in which stormwater and CSO discharges caused medium-high pollution problems impeding the delisting of these areas (Weatherbe and Sherbin 1994). Elsewhere in Canada, the cities with similar pollution problems include Vancouver, Edmonton, Winnipeg, Windsor, Hamilton, Toronto, Ottawa, Montreal, Quebec City and Halifax. Some examples of urban runoff impacts on water quality, aquatic ecosystems, and human health have been reported in the literature and are listed below.

Impacts on water quality are exerted by combinations of physical, chemical and microbiological factors (Chambers et al. 1997; House et al. 1993):

- Physical factors include flow (the effects of which are flooding, erosion, habitat washout), sediment (causing habitat destruction, interference with water quality processes, impacts on aquatic life, transport of contaminants), thermal energy (causing thermal pollution, loss of cold water fisheries) and densimetric stratification (causing the impairment of mixing).
- Chemical factors include biodegradable organics in CSOs (contributing to dissolved oxygen depletion), and nutrients (contributing to eutrophication), trace metals, chloride, POPs, pesticides and hydrocarbons, often occurring in complex chemical mixtures in stormwater and CSOs (contributing to acute and chronic toxicity, and genotoxicity).
- Microbiological factors include bacteria and viruses of fecal origin in stormwater and CSOs (causing beach closures and contamination of shellfish).

The factors listed above can adversely affect the aquatic ecosystem by alterations of chemical dynamics, energy dynamics, food web (trophic dynamics), dispersal and migration of species, disturbance of ecosystem development, loss of critical species, reduced biodiversity, and reduced genetic diversity (Lijklema et al. 1993).

Impacts on human health can be attributed to: (a) contamination of drinking water sources, e.g., by trace substances (Makepeace et al. 1995), (b) contamination of fish and shellfish by pathogens and trace metals in municipal effluents (Chambers et al. 1997), (c) contamination of recreational waters by fecal pollution due to discharges of CSOs and stormwater during wet weather (Health and Welfare Canada 1992), and (d) provision of breeding grounds for disease vectors (e.g., West Nile virus and encephalitis).

It should be recognized that urban runoff quality and its effects are linked to other water quality issues, as shown in Fig. 1. With respect to pollution sources, urban runoff conveys some municipal sewage (in the case of CSOs) and some pollution from industrial sources (accidental spills, illicit discharges, grey waters). Treatment of stormwater and CSOs produces sediment and sludge, which are often disposed of at landfill sites. Urban runoff conveys POPs, pesticides, EDS, pathogens and microorganisms from various urban sources. Stormwater and CSO discharges may contribute to eutrophication and possibly acidification of receiving waters. Finally, urban runoff is impacted on by climate change, with respect to runoff quantity and its distribution in time and space, runoff quality, and operation of runoff control and treatment facilities.

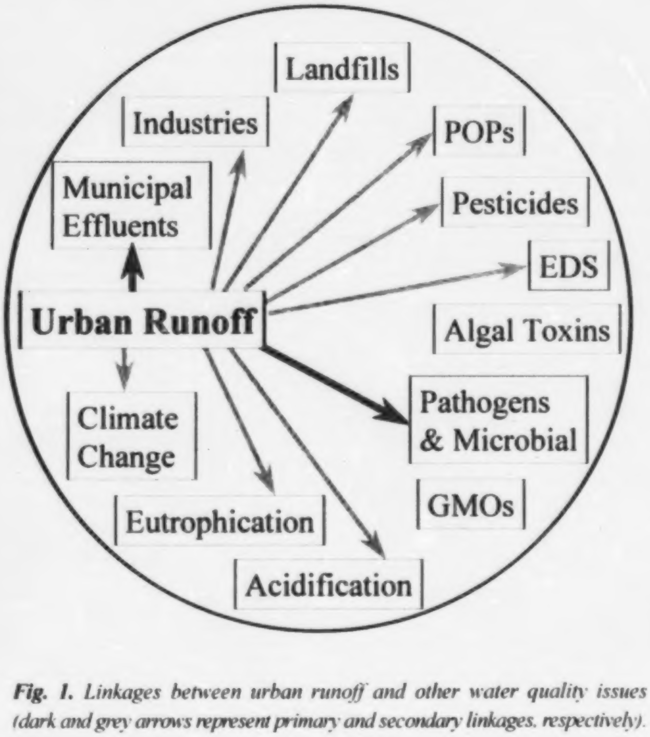

Fig. 1. Linkages between urban runoff and other water quality issues (dark and grey arrows represent primary and secondary linkages, respectively).

Some appreciation of the relative significance of pollutant and/or associated pollution processes can be obtained from U.S. EPA assessment of water quality conditions in the U.S.A. (US EPA 2000). In impaired rivers and streams, the leading pollutants/processes were ranked as follows: 1. siltation (leading in 13.2% of the 850,000 river miles assessed), 2. pathogens (bacteria) (12.3%), 3. nutrients (10.0%), 4. oxygen-depleting substances (8.1%), 5. metals (7.2%), pesticides (5.3%), 6. habitat alterations (5.2%), and 7. thermal modifications (5.2%). With minor exceptions, all these pollutants/processes are associated with urban runoff. The ranking for impaired lakes was as follows: 1. nutrients (leading in 19.9% of the 17.4 million assessed lake acres), 2. metals (12.1%), 3. silt (6.7%), 4. oxygen-depleting substances (6.3%), 5. suspended solids (4.6%), 6. noxious aquatic plants (3.8%), and 7. excess algal growth (3.6%).

Trends

Water and sediment quality, habitat and other uses of urban receiving waters are expected to degrade due to cumulative effects of both controlled and uncontrolled stormwater and CSO discharges from both existing urban areas and future developments.

A long-term demographic trend in urban population, due to overall population increase, and migration from rural to urban areas, will increase demand for water services, including drinking water supply, drainage infrastructure, wastewater management, and protection of receiving waters. Population projections indicate a 5-million increase in the Canadian population in the next 15 years, with most of this increase (80–90%) occurring in urban areas (Statistics Canada 2000). Meeting these demands will become even more challenging, because of increased per capita resource consumption and emissions (e.g., car emissions, heating and air conditioning, personal care products, household and garden chemicals) leading to higher pollution loads and more constituents in stormwater and CSOs. The relative significance of these two diffuse sources is increasing with improved control of point source pollution.

The long-term trend in under-funding of renewal and replacement of drainage infrastructures is expected to continue for at least two decades and will continue to contribute to degradation of receiving waters.

Emerging Issues

It is now recognized that current practices of urban development are not environmentally sustainable with respect to receiving water quality and ecosystem integrity, when assessed on watershed and long-term bases (ASCE 1998; Rijsberman and van de Ven 1999).

The current investment in water planning, management and infrastructure is inadequate to meet the demands of increased population, increased per capita emissions, increased expectations on urban water uses, and increased needs for rehabilitation/replacement of existing infrastructures. An example of inadequate funding can be documented by the aging infrastructure and insufficient maintenance (maintenance programs and their funding are not well established, and there is limited public accountability for privately owned drainage structures and facilities). Poorly maintained drainage systems represent environmental liabilities.

The lack of research is an emerging issue, because of disparity in the severity of problems and challenges posed by new issues, and the current levels of investment in urban water research.

Examples of these upcoming challenges include:

- Climate change; projected changes in precipitation and temperature over the life of some drainage structures may lead to their overloading and poor performance, increased erosion and transport of sediment and landscape contaminants by runoff (resulting in adverse impacts on receiving waters), siltation in receiving waters, disturbance of constructed ecosystems (ponds and wetlands), and hydraulic conveyance problems in coastal areas due to rising lake and sea levels.
- Delayed recognition of impacts (e.g., gradual accumulation of secondary and cumulative impacts in urban developments with and without stormwater control).
- New chemicals, e.g., environmental estrogen, pharmaceuticals, personal care products, and other substances often found in complex chemical mixtures in surface waters and municipal effluents.
- Spread of infectious diseases by vectors inhabiting urban wetlands and impoundments.
- Potential GMO use in urban landscaping and associated effects on the environment.

Impacts on urban waters will also occur due to additional activities outside of urban boundaries. Adding to these stresses are upstream and downstream development and water uses (e.g., boating).

Knowledge and Program Needs

The knowledge requirements span the breadth of fields of science, social science, engineering, planning and management.

The first requirement is a better understanding of urban runoff and associated processes in terms of:

- Sources, source inventories, pathways and fate of contaminants as well as microbial pollutants in the urban environment.
- Regional diversity in processes due to climate, surficial geology, urban development practices, etc.
- Effectiveness of control measures in protection of receiving waters and both aquatic and terrestrial ecosystems, and human health, by policies and source controls, site best management practices (BMPs), community BMPs, and watershed-level measures. This knowledge should contribute to the eventual substitution of effluent criteria with ecological risk assessment of receiving waters.
- Increased vulnerability of ecosystems by secondary effects of stormwater management measures (risk of contamination of groundwater, heating of ponds and wetlands, release of contaminants from sediments, and risk to aquatic life and wildlife through uptake of contaminants and exposure to pathogens).
- Cumulative and combined effects of urban effluents on receiving waters and their ecosystems, with respect to intermittent exposures to varying concentrations.

To acquire this understanding as well as to establish time trends, the following data/monitoring needs are identified:

- Chemical and microbiological descriptors of stormwater and CSOs (deficiencies in the available data—limited data on such constituents as pesticides and nutrients; inorganic and limited trace organic [POPs] data are 20 to 25 years old, since then analytical capabilities have improved and sources of these chemicals have changed; insufficient geographic coverage; and, minimal data are available on CSOs).
- Status/performance of the existing drainage systems (extending from catchment headwaters to receiving waters).
- Cumulative long-term impacts of urbanization (e.g., geomorphologic changes and habitat degradation).
- New chemicals and/or chemicals newly identified under CEPA (EDS in CSOs and runoff, including natural and synthetic hormones and certain industrial chemicals that have been identified in sewage effluents and are capable of estrogenic effects; pharmaceuticals and personal care products; road salts; and, used crankcase oil in runoff).

The second requirement is research on the integrated management of urban water, including better management of runoff and CSOs, in support of total urban water cycle management (Lawrence et al. 1999). Products of this research would include:

- Sustainability criteria for urban water management.
- Advancement of pollution source controls in urban areas, including research on roles of public education, awareness and participation in source control programs.
- Protocols for protection of urban drinking water supplies from all hazards including urban runoff.
- New approaches to urban development based on a scientific understanding of processes and providing maximum protection of the environment.
- Adaptive approaches to urban water management, in light of climate change and other uncertainties.

The third requirement is research in support of infrastructure renewal, which would include:

- Development of national standards for environmentally and economically efficient design and operation of urban drainage systems (considering structure life expectancies and discount rates).
- Assessment of alternative modes of infrastructure ownership and operation (ownership and asset management, provision of services by the public or private sector, establishment of drainage utilities/agencies, and user service fees).

To deal effectively with the existing and emerging issues in management of urban waters, the Federal Government should provide leadership by initiating and directing research on integrated water quality management. This would entail establishing strategic alliances of all levels of government, academia, the public, NGOs, and the private sector. The proposed research would be based on broad applications of information technology and would provide tools to assist municipalities in implementing sustainable practices in water management. Towards this end, the following two recommendations are made:

- Develop a knowledge base and tools on urban water processes, data and monitoring, integrated urban water management and planning infrastructure renewal. The progress under this initiative would be accelerated by developing a policy on integrated urban water management, considering the whole watershed and integrating the needs of the urban population and the protection of urban ecosystems.
- The initiative targeting urban areas should be part of a broader initiative on integrated water quality management, encompassing principal sources, both point (industrial and municipal, landfills) and non-point (agricultural and urban), and principal receiving water stressors (including algal toxins, EDSs, trace metals, nutrients, pathogens and microbial pollutants, pesticides, POPs, GMOs, eutrophication, acidification, and those associated with climate change).

Flooding and erosion impacts of urban runoff can be lessened by effective stormwater management.

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12. LANDFILLS AND WASTE DISPOSAL

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Current Status

Canada ranks among the highest producers of solid waste per capita in all of the industrialized world. Although Canada is viewed as a country of abundant fresh water resources, in reality we are facing a mounting threat as a result of improper waste management. Canadian citizens have been directly impacted by the consequences of improper waste disposal, and many of these have drawn widespread media attention. In the spring of 2000, seven people died and over 2000 took ill as a direct result of improper disposal of animal wastes in Walkerton, Ontario. Important drinking water sources at Elmira and Smithville, Ontario; Abottsford, B.C.; and Ville Mercier, Quebec, have been destroyed as a result of poor waste disposal practices. Hazardous waste from the Sydney tar ponds, Nova Scotia, have contaminated groundwater and surface water in highly populated areas, and has resulted in the release of pollutants to the ocean. Millions of litres of contaminated water flowing daily from the waste rock of Britannia Mine, near Squamish, B.C., have caused large areas downstream to become void of life. These incidences will become more frequent in the future, unless Canada immediately develops and implements a comprehensive waste management plan.

Wastes are a part of life. They are produced as by-products of agricultural, industrial, commercial and domestic activities. These wastes are recycled, incinerated or treated, or disposed. Disposal approaches range from the use of highly engineered facilities to simple landfilling and spreading operations to deep-well injection. Canada has a wide spectrum of approaches in managing wastes within primary waste streams. Canadians are one of the largest producers of waste in the world. 1988 statistics (Environment Canada 1991) show that Canada produced 30 million tonnes of solid waste annually, amounting to about 1.8 kg per day per person or twice as much produced per person in Sweden.

The main threat to water quality due to the disposal of wastes focuses on the groundwater environment. Surface water contamination also occurs as a result of direct runoff from waste sites to streams, lakes and wetlands, and indirectly as contaminated groundwater discharges to surface waters. The contamination of groundwater has many factors which makes it very different from surface water contamination. Because we cannot observe groundwater, we typically discover that the groundwater is contaminated once a well or surface water body becomes contaminated. Surface water contamination occurs quickly and can be stopped at the source. However, groundwater contamination may commence years after the waste source is in place. The slow release rate causes it to take years to thousands of years to move through the groundwater flow regime, and groundwater can be difficult, if not impossible to remediate, and prohibitively costly to remediate. Ultimately all contaminated groundwater will discharge to surface water. Thus, should serious groundwater contamination occur, the destruction of drinking water supplies and aquatic ecosystems occurs for decades to hundreds of years.

Municipal/Hazardous/Industrial Solid Waste

Solid waste is predominantly composed of domestic waste, hazardous waste, industrial waste, contaminated soils and building debris. It is estimated that hundreds of landfill sites are located within Canada. This estimate is considered low as it does not account for small landfills, landfills not registered with the appropriate agency, or abandoned landfills. Disposal options for municipal wastes range from disposal in engineered facilities to disposal in open excavations, with regulations and guidelines varying across Canada. The siting, design and monitoring of solid waste facilities is relatively well understood. It is now accepted that all landfills will eventually release leachate to the surrounding environment and therefore all landfills will have some impact on the water quality of the local ecosystem. Traditionally, solid waste landfills are monitored for nutrients, heavy metals, major ions and volatile organic compounds (VOCs). Many of these constituents have been observed in aquifers at distances up to several kilometres from the landfill source. As an example of the cost of containment failure, PCB waste which leaked to groundwater from a waste transfer facility at the town of Smithville, Ontario, between 1978 and 1985, forced the closure of the town's water supply wells. After spending over $55,000,000, the shallow contaminated soils have been removed, a new water supply system for the town of Smithville has been installed, and groundwater studies have been conducted. However, long-term threat from contaminated groundwater still exists and after 15 years of study we are just beginning to gain the knowledge necessary to understand how the waste is moving through the subsurface and what we can do to remove it (Novakowski et al. 1999).

Mining Waste

Mining waste is generated through the processing of base metal and gold-bearing ore, coal, potash and tar sands. The waste is disposed of in piles, geographic depressions, or constructed impoundments which can cover thousands of hectares. It is estimated that mining activities in Canada have produced at least 350 million tonnes of waste rock, 510 million tonnes of sulphide tailings and more than 55 million tonnes of other wastes. More recent disposal methods include subaqueous disposal and as mine backfill. If the waste contains sulphide minerals, such as pyrite, sulphide oxidation reactions occur, releasing acidity and heavy metals to the groundwater and surface water. Currently the design of mine disposal sites is determined by geotechnical factors rather than water quality issues. Recent advances by Canadian researchers have shown that the disposal of mining waste may have a long-term detrimental impact on the surrounding ecosystem (Bain et al. 2000). These effects have been projected to last decades to centuries to even millenia due to the slow rate of oxidation and transport of oxidation by-products (i.e., acid, heavy metals, arsenic, etc.) through the underlying geologic media. Concentrations of contaminants can exceed drinking water and aquatic limits by several orders of magnitude.

Agricultural Waste

On a national basis, the disposal of livestock waste associated with cattle, swine, and poultry farming, occurs over an extremely large area throughout Canada. The primary contaminants associated with manure include nitrate and ammonia, coliform bacteria, phosphorus, endocrine disrupters and other animal pharmaceuticals. Both the land use and waste management practices commonly employed on farms throughout Canada have impaired the quality of water resources on a regional basis (Rudolph et al. 1998). In a recent survey of farm drinking wells in Ontario, approximately one well in three was found to contain at least one contaminant commonly associated with agricultural activities, including nitrate or bacteria (Goss et al. 1998). Runoff of nutrients and microbes from manure have caused numerous incidents of serious contamination, for example, fish kills in PEI and Ontario, cases of eutrophication of surface water all across Canada, and the steady rise in nitrate levels in the tributaries of Great Lakes during the past 20 years. Environment Canada (1998) reported that eutrophication due to manure runoff was the principal cause of fish kills in Ontario. Current management practices throughout most of Canada involve the temporary storage of raw manure in open barnyards, earthen lagoons, or concrete tanks. Manure is subsequently spread on cultivated fields at different times of the year as a method of final disposal. Surface runoff from barnyards and storage facilities leads to direct release into surface water and groundwater. Once the contaminants have entered the groundwater system, they can be intercepted by local farm wells, municipal wells (as was the case at Walkerton, Ontario) and surface water courses.

Municipal Biosolids and Septic Systems

Urban sewage, consisting of a mixture of solid and liquid wastes, typically undergoes primary treatment in sewage treatment plants. The treatment plants are designed to remove biosolids and a fraction of dissolved components from the wastewater. The biosolids generated from the treatment process are typically disposed in landfills. However, huge quantities are still spread on agricultural land. It is estimated that 80% of Ontario's municipalities dispose of over 1.5 million tonnes of biosolid on 13,000 hectares of land each year by spreading it on agricultural land (Coote and Gregorich 2000). Biosolids contain elevated concentrations of nitrogen, phosphorus, metals, and other residues of often unknown composition. Depending on the degree of treatment, biosolids may also contain elevated concentrations of pathogens, including fecal coliform, *E. coli*, viruses and protozoa. There are a series of guidelines and regulations in Canada recommending best practices for land spreading of biosolids. These guidelines and regulations may not provide adequate protection to prevent exposure to humans, livestock, soil organisms, and crops to pathogens or undesirable uptake of metals and other constituents into food crops and other ecosystem impacts. When applied in tile-drained areas, pathogens may survive the downward transport to the drain (typically 40–50 cm below surface) and be discharged to adjacent streams or drainage ditches.

Sewage generated in non-urban settings is typically disposed using on-site treatment systems. Most commonly, the wastewater is released to septic tanks where anaerobic digestion processes take place, and the decant water is released to tile lines where infiltration to the subsurface is promoted. The solids slowly break down in the septic tank or are pumped out and spread on fields or treated in wastewater treatment plants. In Canada, there are a variety of alternative disposal practices followed which provide comparable or improved degrees of treatment to conventional practices. Most on-site wastewater disposal systems involving discharge to the subsurface result in the release of nutrients, metals, pathogens, surfactants, medications and other constituents to groundwater (Robertson et al. 1998). The resulting plumes can discharge to surface water bodies over time. Plumes of septic-system derived contaminants often contain concentrations of nitrate above drinking water guidelines, at times many hundreds of metres from the source (Ptacek 1998). On-site wastewater disposal represents the largest volume of wastewater discharged to the subsurface in Canada. As with agricultural waste, the short-term fate and transport of the traditional contaminants, such as nitrate and phosphate, are relatively well understood. However, the long-term impacts of these traditional contaminants are poorly understood as are the fate and transport of bacteria, viruses and other substances that have not been analyzed to date.

Other Wastes

The petroleum industry can produce a variety of wastes. During the drilling of oil and gas wells, the sump pits typically contain brines with very high concentrations of salts and metals which leach to the underlying water table. There are hundreds of thousands of these sites located in Saskatchewan, Alberta and B.C. These have not emerged as a major threat because bentonite used in the drilling process will entrap the brine, and recent drilling techniques used above-ground tanks, from which the waste is disposed to landfills. Another by-product, sulphur, is extracted during the processing of natural gas and stored in large piles. Runoff which is not captured can cause elevated levels of sulphate in groundwater, however the groundwater near many of these sites typically has naturally high sulphate levels. Many wastes from the petrochemical industry are disposed through deep wells in Ontario and Alberta. Although this is generally a safe means of waste disposal, when improperly sited or constructed, extensive groundwater and surface water contamination occurs if the waste is able to migrate to the surface. Problems with corrosion of the well casing and seal in abandoned wells may produce a pathway for the upward migration of hazardous wastes and oilfield brines to shallow aquifers used as sources of drinking water. This was the case at Lambton County, Ontario, during the 1970s (Vandenberg et al. 1977). Processing plants also produce wastes at their flare pits. These wastes, which include produced water (brine), sludge, PAHs, metals, and oils, accumulate over time. Most of these pits have been found to leak and cause groundwater contamination.

Considerable waste sediment is generated during the dredging of harbours and channels. This sediment is generally used as fill along shorelines, but because some harbours are contaminated (e.g., Hamilton, Halifax, St. John's) special disposal facilities are required. Similarly, considerable fill is generated from the disposal of old buildings, roadways, and building excavations. If the material is uncontaminated it is used as shoreline fill or disposed in municipal landfills. If classified hazardous, it is disposed in hazardous landfills. The runoff of excess road salt has caused extensive contamination of surface and ground waters. Levels of road salt in the Waterloo Aquifer are rising and may eventually render the aquifer unfit as a source of drinking water. It is a common problem adjacent to just about every road in rural Canada. In urban areas storm sewers dramatically limit groundwater contamination, but discharge from the sewers causes extensive contamination of surface waters. High-level radioactive waste generated in nuclear reactors poses a very serious health risk and very long-term problem. Because of this, AECL is conducting an extensive program to manage and dispose of this type of waste.

Trends

The legacy of solid waste management in Canada has left a complex series of water quality problems, many of which we are just beginning to understand. The problems are not entirely due to poor management practices of the past, but are due to the evolving nature of the problem which causes us to look for new contaminants and institute new disposal practices. Many of the contaminants of the future currently exist, and perhaps have existed in water for years, we just have not begun to look for them yet (e.g., emerging POPs, pharmaceutical compounds). The contaminants which we currently know about, will also continue to cause major problems and numerous challenges. Predicting the significance of these contaminant releases on the long-term health of the aquatic environment, developing methods to minimize these future impacts, and formulating an effective regulatory framework that ensures effective management, represent the most immediate tasks at hand.

Municipal Solid Waste

As Canada's urban population grows, so does the amount of municipal waste produced. It was estimated that in 1995 Metropolitan Toronto, York, Durham and Peel regions disposed of 2.0 million tonnes of municipal waste, and another 0.95 million tonnes of private waste was exported from this area (Golder Assoc. Ltd. 1996). The lengths to which municipalities may have to go to dispose of their municipal waste was dramatically illustrated by the City of Toronto proposal last year to send its municipal garbage 600 km north to the abandoned Adams Mines near Kirkland Lake. The garbage would fill the mine's pen pits and rise another 35 m above ground surface, but the site would only have a life-span of 20 years (Golder Assoc. Ltd. 1996). Proposals to reduce wastes through recycling or at the source (e.g., less packaging) will only slightly reduce the rate of increase. Public pressure is causing the siting of landfills to become difficult. With the realization that all engineered facilities will likely fail, releasing leachate to the ecosystem, numerous issues have begun to emerge. Regulations (if any) on the siting, design and operation of facilities vary across the country thus creating a process that is vulnerable to political factors rather than a process that is based on technically sound criteria. Inevitably the leachate from the landfill will impact the water quality and thus require the installation of an expensive and often ineffective remedial system that requires long-term operation. The leachate may also change the conditions within the receiving aquifer or surface water body which may result in enhanced transport of contaminants. The potential influence of these changes on the mobility of these contaminants is not well understood. These factors along with the introduction of new chemicals and compounds will provide challenges for protecting water quality.

Agricultural Wastes

The number of feedlots in Canada increased dramatically between 1990 and 2000. As agricultural operations evolve, pressure to increase animal density on farms will lead to increasing volumes of manure wastes and the need for the development of appropriate management protocols to minimize future risks to water quality. Even if all sources are removed, the slow release and movement of associated contaminants from the existing mass in the subsurface will continue with increasing impacts on water quality over a very long time. As a result, significant degradation of regional water quality resulting from manure management practices may be anticipated regardless of the implementation of alternative management strategies. The occurrence of endocrine disrupting substances and animal pharmaceuticals in groundwater and surface waters in rural areas may be a significant issue. As yet, very little data exists to evaluate these risks. The increasing release of bacteria and viral species including pathogens may result in more frequent cases of microbial contamination, particularly in the groundwater environment. The development of alternative waste management practices, that will be both effective and inexpensive will be actively sought by the agricultural community. Both the development and implementation of these practices will require collaboration between government, researchers, and the private sector.

Mining Waste

Although the number of mines in Canada has remained essentially constant during the last decade, there is a trend towards larger mining operations which produce larger volumes of waste. The emerging issues associated with mining waste are the need to develop and implement improved disposal techniques to reduce the oxidation of sulphide minerals within the waste and to develop cost-effective treatment methods for existing sites. Other emerging issues include the potential release of heavy metals and oxyanions (i.e., arsenic) from subaqueous disposed mine waste as well as geochemical reactions occurring at the surface water-groundwater interface. Abandoned mine sites represent long-term liabilities to various jurisdictions and further study is needed to fully understand the impact on future generations.

Hazardous/Industrial Waste

Canada and Ontario continue to undertake actions to reduce the levels of hazardous waste disposed within the Great Lakes region (COA 1997). Emerging issues associated with hazardous/industrial wastes are the issue of harmonization of regulations and guidelines between jurisdictions as well as the importation of hazardous waste from other countries such as the United States. Between 1998 and 1999, importation of hazardous wastes from the United States has increased by 18% to 663,000 tonnes prompting Minister Anderson to call for stricter standards (Judd 2000). Factors affecting the importation of hazardous wastes include liability issues, exchange rates and less restrictive regulations associated with the number and type of wastes allowed to be disposed of within landfills. Other issues include the effectiveness of barrier systems over a prolonged period of time (>50 years) and the influence of new chemicals and compounds on barrier integrity. Issues on the transport of dissolved and free-phase chemicals and compounds within a variety of geological materials have also been raised. The contamination of groundwater in Lambton County, Ontario, and the St. Clair River by hazardous waste injected into disposal wells (Vandenberg et al. 1977) is an excellent example of the extent of water quality problems which can result from a lack of knowledge. Disposal wells were constructed and waste injected following the regulations and best knowledge at the time. However, it was not realized that waste fluids would migrate to the surface through abandoned oil and groundwater wells, causing a major problem that still exists today.

Municipal Biosolids and Septic Systems

As the population in Canada increases, the mass of solid and liquid wastes generated will increase, resulting in larger volumes of wastewater released to the subsurface and the generation of larger volumes of biosolids from treatment plants. The number of septic systems will continue to increase dramatically with population increases in rural residential areas, recreational areas, and lakefront properties, and conversion of seasonal cottages to year-round homes, which are served by individual septic systems. Most regulations rely on the use of setback distances to prevent the uptake of bacteria in drinking water supplies, or the release of bacteria and nutrients to surface waters. These setback distances provide adequate protection in many geological materials to prevent large-scale disease outbreaks. There are, however, a number of aquifer types where the transport of viruses over long distances has been documented, and where infection of humans has occurred. Coarse-grained sand, gravel, and fractured bedrock aquifers are particularly susceptible to widespread transport of viruses and other pathogenic organisms. A number of physical, chemical and other aquifer properties have been identified as factors controlling the transport of viruses in aquifers. Information gained through research programs conducted outside of Canada can likely be transferred directly to evaluate the potential threat of pathogen transport in aquifers in Canada, however there are a few issues unique to the Canadian environment such as the much lower temperatures which might sustain the viability of pathogenic organisms over longer transport distances. Other information gaps relate to the transport of constituents that are newly recognized as being potential threats to human and ecosystem health. These include the unknown fate of medications, surfactants, food additives and natural hormones in the subsurface, and the uptake of these constituents in wells, or release to surface waters.

Knowledge and Program Needs

Considerable experience has been amassed over decades of waste management activity in Canada and elsewhere. The understanding of the complex array of issues associated with current management practices and historic activities has just begun to develop. This has been particularly true in Canada because of the enormous land and water resources available and the concept that these resources are essentially endless and not susceptible to environmental impacts of waste disposal as seen in the rest of the world. We can look back at many of our serious water contamination problems and identify poor disposal and management practices. However, many problems were not the result of bad management practices (in fact they followed existing regulations and engineering practices), but due to a lack of knowledge, which is now available. As such, several key areas require additional understanding and study.

Municipal Solid Waste

The major knowledge gaps in our understanding on municipal solid waste disposal include:

- Long-term integrity of liner, cover and leachate collection systems.
- Long-term aging reactions within the waste and receiving aquifer or surface water.
- Mobility and degradation of new chemicals and compounds, such as EDS, POPs, etc.
- Interaction between new chemicals and compounds.
- Methodological issues related to the detection and quantification of new chemicals.
- Effective implementation of aquifer remediation and leachate treatment systems.
- Role of changing geochemical environments on naturally occurring constituents.

Agricultural Waste

The major knowledge gaps in our understanding on agricultural waste disposal include:

- Fate and transport of pathogens, EDS, and pharmaceuticals.
- Monitoring and inventory of existing contaminant mass in the subsurface.
- Development of best management practices, especially at a watershed scale.
- Slow release to the surface water courses through seasonal fluctuations.

- Investigation of alternative waste disposal methods (as being implemented in other parts of the world).

Mining Waste

The major knowledge gaps in our understanding on mining waste disposal include:

- Release of contaminants from waste disposed of in underwater environments and as mine backfill.
- Attenuation and release mechanisms in aquifers impacted by mining waste.
- Long-term release of metals from waste-rock piles and tailings.
- Transport and fate of contaminants across the groundwater-surface interface.
- Effect of chemical additives on the mobility of heavy metals and other contaminants of concern.
- Long-term stability of engineered impoundments and piles.

Hazardous/Industrial Waste

The major knowledge gaps in our understanding on hazardous/industrial waste disposal include:

- Long-term integrity of liner/cover system.
- Co-disposal effects on transport and degradation processes.
- Degradation and transport properties of new chemicals and compounds.
- Availability of analytical chemistry methodology.
- Effects of waste types on barrier integrity.
- Influence of climate effects on disposal methods.
- Long-term integrity of steel casing and concrete plugs in abandoned disposal, oil and gas wells to maintain a seal which prevents upward migration of contaminants.
- Comprehensiveness of leachate treatment systems.

Municipal Biosolids and Septic Systems

The major knowledge gaps in our understanding on municipal biosolids and septic systems include:

- Long-term fate of accumulated nutrients and metal and release into drinking water supplies.
- Fate of pathogenic organisms in different soil types with particular attention to cold regions.
- Fate of pathogenic organisms applied to tile-drained fields.
- Transport and fate of EDS, pharmaceuticals and new chemicals as they are introduced.
- Development of alternative disposal methods to optimize removal of all undermined constituents.

Science

- Research into long-term processes and reactions.
- Awareness of what to look for.
- Improved analytical and field methods.
- Close the gap between science and policy.

Policy

- New regulations, rather than guidelines.
- Harmonization of regulations and guidelines among all levels of government.
- Implementation of effective groundwater protection and watershed management practices.
- Improved monitoring procedures.
- Realistic bonding ($) to ensure funds available to deal with long-term problems and abandoned sites.

Education

- Recognition of the extent of the problem.
- Need to deal with problems at the source rather than away from source.
- Focus on protection/prevention rather than remediation.

Abandoned mines are one of the sources with potential to release heavy metals and other contaminants into ground and surface waters.

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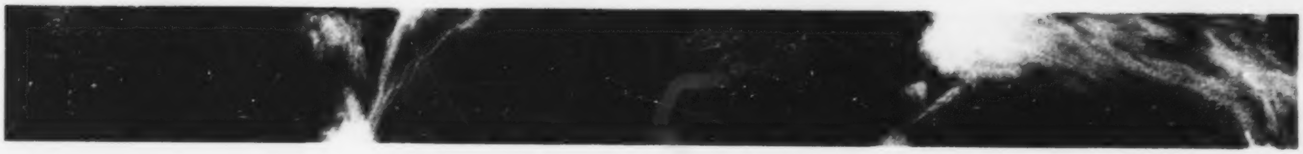

13. AGRICULTURAL AND FORESTRY LAND USE IMPACTS

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Current Status

Land use and land management practices affect the quantity and quality of runoff water and, in turn, the water budget, water chemistry and biodiversity of aquatic organisms in receiving waters. In Canada, approximately 12% (119 million ha) of the total land base is currently managed for timber harvest, another 7% (68 million ha) is used for farming and an additional 1% (7 million ha) is in urban and industrial development.

Canada's forests, which represent 10% of the world's forests, cover nearly half of the Canadian landscape—some 418 million ha. Forests are a dominant feature of Canada's economy, culture, traditions and history. They represent an integral part of our natural environment and life-support systems. Forests also contribute 10% of Canada's gross domestic product in the primary production sector. In addition to their socioeconomic value, forests purify water, moderate climate, regulate water flow, provide habitat for wildlife and stabilize soil. Canada is one of the world's largest suppliers of wood products. Some 245 million ha (or 59%) of Canada's forestland are capable of producing commercially valuable timber, of which 119 million ha are actively managed for timber harvest (CCFM 2000). Changes in forest soil characteristics and forest hydrology following timber harvest have raised concerns about the quantity and quality of water supplied to nearby lakes, streams and wetlands and the effects of these water quality and quantity changes on aquatic organisms.

Agricultural production is the transformation of solar energy and nutrients into crops, much of which is then fed to livestock to yield meat, dairy and poultry products. Agriculture represents 29% of Canada's gross domestic product in the primary production sector, second after mining and energy (29%). Of the total agricultural land base, 83% is in the Prairies and about 13% is in Ontario and Quebec. Approximately 46 million hectares are improved land (i.e., cropland and summerfallow) while the remainder (22 million ha) is unimproved land, essentially pastures. The last century saw great development in many agricultural technologies such as high-yielding crop varieties, chemical fertilizers, pesticides, irrigation and mechanization. These developments have resulted in agricultural operations becoming increasingly specialized such that the emphasis is either on livestock or intensive cash cropping (DeKimpe et al. 2000). Whereas mixed farms were able to efficiently recycle animal manure by applying it to agricultural fields, geographic separation between intensive livestock operations and cash-crop farms has resulted in manure being regarded in some locales as a waste requiring disposal rather than as a fertilizer and soil amendment. In contrast, cash crop farms need to apply large amounts of manufactured fertilizers to meet crop requirements. This inequitable distribution of resources, along with the cultivation of marginal land caused by loss of prime agricultural land to urbanization, has raised concerns about the effect of nutrients and pathogens from manure and chemical fertilizers on air and water quality.

Two key science questions underlie concerns about sustainability of healthy waters in agricultural and forested landscapes: (1) has human activity affected the availability of the quantity and quality of water and the aquatic life supported by this water, and (2) how will new or additional stresses affect existing conditions?

Forestry Sector

The greatest threats to forest ecosystems today are conversion to other forms of land use and fragmentation by agriculture, logging, and road construction. Logging and road construction, in turn, open intact forest to settlement and increases in hunting, poaching, fires, and exposure of flora and fauna to pest outbreaks and invasive species. In 1999, about 119 million ha (or 28%) of Canada's forestland were actively managed to produce timber. About 1 million ha (or 0.8% of this commercial forest area) was harvested, removing approximately 174.5 million m^3 of wood. About 60% of the area harvested was left to regenerate naturally, usually after some form of preparatory site treatment; the remaining area was planted with seedlings or seeded. Areas affected by fire (1.7 million ha in 1999), insects (5.1 million ha in 1999), and disease were also left to regenerate naturally.

Undisturbed forests efficiently cycle water as well as large quantities of nitrogen and other nutrients with very small losses to surface and ground waters. Streams draining undisturbed forest generally have high water quality with low concentrations of dissolved nutrients and suspended sediments. Forest management practices that disrupt the cycle of nutrients between the soil and trees may increase runoff and concentrations of dissolved nitrogen, base cations and, to a lesser extent, phosphorus in adjacent streams and lakes. Timber harvest, when conducted near stream banks, results in an increase in water temperature due to removal of the forest canopy. In addition, removal of forest vegetation can increase soil erosion, resulting in increased sedimentation and detrital input to streams and lakes. Nutrient, cation and sediment inputs to streams and lakes as a result of forest management practices have been defined for relatively few sites in Canada. The effect of forest management practices on water quantity and quality is difficult to assess, therefore, and confounded by climatic, topographic and vegetation diversity across the country.

Agricultural Sector

Over the past 40 years, the number of farms in Canada have declined, but those that remain have become larger and more productive. This transformation was made possible by greater mechanization, the use of mineral fertilizers and pesticides, new and better crop varieties, and innovative farming practices. Over time, some of these advances have clearly compromised environmental health, including water quality. Agricultural impacts on water resources are caused by:

- The need for additional water (semi-arid landscapes) or to route excess water off fields (humid landscapes). These practices have had positive effects on water quality (e.g., proper drainage reduces surface runoff and erosion, and loss of nitrogen by denitrification) but also detrimental effects (e.g., increased leaching or runoff of agrochemicals [nutrients and pesticides] and bacteria to surface and ground waters).
- The use of additional nutrients (in the form of mineral fertilizer, manure, compost, sewage sludge) to increase crop productivity. This practice has led in certain parts of Canada to a nutrient surplus in the soils with the potential loss of nutrients to surface and ground waters.
- The use of pesticides (fungicides, herbicides and insecticides) for disease, weed and insect control. Although the use of pesticides has increased the efficiency of fertilizer use, this practice has resulted in pesticide losses to the atmosphere and subsequent deposition from the atmosphere to surface water and non-agricultural lands, as well as runoff and leaching to surface and ground waters.
- Alterations to soil conditions caused by tillage and cropping patterns. Certain of these practices may cause soil degradation, which can lead to less infiltration of water into soil and, thus, increased runoff and movement of nutrients and pesticides to surface waters. Over the past 40 years, tillage practices have moved toward greater use of conservation practices, including no-till. These tend to encourage infiltration rather than runoff.
- Drainage of wetlands and canalling of streams has increased the area of agriculturally productive soils, but modified local ecosystems and changed the pattern of water partitioning between evaporation, streamflow and infiltration.

Trends

Forestry Sector

In 1995, about 995 thousand hectares of forest were harvested, representing 0.4% of Canada's total timber-productive forest area and 0.8% of the accessible timber-productive forest area (CCFM 2000). Softwood species (e.g., pine, spruce) accounted for more than 86% of Canada's total commercial timber harvest in 1995. Although total harvest levels for softwood in 1995 were below the allowable annual cut (AAC) on a national basis, the harvest reached the AAC in some regions while in other regions, timber supply shortages were reported. The hardwood component (e.g., poplar, maple) of the annual harvest increased between 1990 and 1995 by over 6%—representing an annual increase of 1.3%. This trend is expected to continue in order to meet market demand.

Timber harvesting methods include clear-cutting, selection cutting, shelterwood cutting and seed-tree cutting. Clear-cutting was the most widely used method in 1995. Because of environmental impacts associated with large cutblocks (e.g., forest fragmentation, increased potential for changes in runoff and water quality), forest management practices in Canada are shifting toward smaller cutblocks with irregular boundaries interspersed with uncut forest to create greater spatial and age diversity in the landscape. Clear-cutting, because it does not mimic the ecological effects of fire, sometimes results in fundamental ecological shifts in fire-dominated ecosystems (Carleton and MacLellan 1994).

Climate change could have serious ecological and socioeconomic implications for Canada's forests. Climate warming will not only affect the frequency and severity of natural disturbances (e.g., wildfire and outbreaks of spruce budworm) but will also influence management practices such as harvest schedules, regeneration and afforestation, and forest protection. Climate warming may result in changes in the water table with resultant changes in storage and release of nutrients and metals from forest soils and wetlands.

Agricultural Sector

The last century saw great development in agricultural technologies and production. Between 1950 and 1985, the success of the Green Revolution in reducing food shortages in several parts of the world was linked primarily to new crop varieties designed to maximize yields, facilitate multiple cropping, and resist diseases. To achieve the full potential yield of these improved varieties and to protect them against diseases and pest infestation, it was essential to provide crops with chemical nutrients, the consumption of which rose more than ninefold, and to employ pesticides, the use of which increased 32 times.

With little prospect for the development of significant areas of new farmland, yet continuing government policies encouraging more food production, agri-food production in Canada has increased in efficiency during the past two decades (DeKimpe et al. 2000). For example, grain production in Canada increased by 2.4-fold between 1961 and 1986 on a cropland base that increased by only 1.6 times (from 18 to 28 million ha). This production growth was achieved through improved crop strains and increased fertilizer use (from 2.0 million tonnes in 1967 to 4.2 million tonnes in 1987 of nitrogen, phosphorus and potassium fertilizers) and pesticide application. A 2.9% increase in milk production in Ontario between 1951 and 1991 (from 2.39 to 2.46 billion litres) was achieved using 849 thousand fewer animals and 573 thousand fewer hectares, and resulted in a 42% decrease in dairy cattle manure (from 21.4 to 12.5 million tonnes). Much of the grain used as feed was obtained from higher-yielding and more disease-resistant crops and employed farming practices that required less fossil fuel use (i.e., grain corn production increased from 3.3 to 5.3 million tonnes between 1975 and 1991 whereas litres of diesel fuel equivalents declined from 292 to 191 million over the same period). Although certain efficiencies in agri-food production have reduced threats to water quality, other efficiencies have increased the risks posed to water quality. For example, greater use of mineral fertilizers and pesticides and greater manure production can increase the risk of water contamination unless these substances are adequately managed. The situation is further exacerbated by the growing trend toward application of sewage sludge to cropland.

Demand for water is growing in Canada by the agricultural community (particularly to meet irrigation needs) as well as by other sectors. Competition for the finite supply of water, particularly in water-short areas such as the Prairies and the interior of British Columbia, or at times of drought in areas such as Ontario, has already given rise to conflict among users (Kienholz et al. 2000). This situation is likely to become worse in the future under possible climate change scenarios. Global warming scenarios indicate that drought will be more frequent and severe where precipitation does not make up for the increased water losses from evaporation. However, the uncertainty in climate models, particularly related to precipitation, makes it difficult to predict confidently where, when, and to what degree droughts will take place in the future. If the significant declines in streamflow, groundwater levels, and lake levels are realized, there will be greater potential for conflict over water allocation and for deterioration in water quality caused by reduced water availability for dilution of pollutants.

Emerging Issues

Forestry Sector

Physical Properties of Lakes and Streams

Timber harvest can increase water yield, suspended solids and temperature in streams. In general, total runoff increases with forest disturbance due to reduced interception and transpiration by the forest canopy. Annual peak discharge shows, however, a variable response with some studies reporting increases and others decreases, possibly due to differences in climate, geology, topography, vegetative cover, soils, and the timber harvesting method. For example, water yield and peak flow returned to preharvest conditions within three to six years for two northern hardwood streams (White Mountains, New Hampshire; Martin et al. 2000) whereas high runoff is predicted to persist for decades after forest clearance in the boreal forests of eastern Canada (Plamondon 1993). Increased stream discharge may be associated with higher sediment yields, although this may be controlled by employing best management practices (Martin et al. 2000).

Chemistry of Lakes and Streams

Loss of forest cover can disrupt biogeochemical cycles as a result of alterations of chemical sinks and sources, increases in soil temperature and humidity, changes in soil structure caused by logging equipment, and flushing of chemicals (e.g., nitrogen, phosphorus, dissolved organic carbon and major ions such as calcium, potassium and sulfate) from surficial soils. The impact of timber harvest on concentrations of dissolved solids depends on the intensity of harvest, forest cover, soil type, and slope steepness. Impacts will also vary with the level of protection afforded during disturbance, through the use of lakeshore or streamside reserves and buffer strips. Increases in water yield following timber harvest may further exacerbate nutrient and ion export. Our understanding of the effects of timber harvest on biogeochemical cycles is not sufficient to predict the magnitude and duration of environmental responses to logging. For example, clear-cutting around deep headwater lakes in northwestern Ontario caused only modest changes in nutrient and major ion concentrations (Steedman 2000) whereas concentrations of most dissolved substances were substantially higher in central Quebec lakes affected by wildfire or harvesting (Carignan et al. 2000). In aspen-dominated sites on the Boreal Plain, phosphorus but not nitrogen concentrations in lake water appear to be enhanced by winter harvesting practices (Prepas et al. 2001). Although the differing response between lakes in these three ecoregions may be due, in part, to differences in lake morphometry, drainage ratio and water renewal times, such variability is typical for the limited number of studies on timber harvest impacts on aquatic ecosystems in Canada.

Logging has also been found to cause increased concentrations of mercury in fish. Comparison of total mercury concentrations in northern pike (*Exos lucius*) from Boreal Shield lakes in Quebec showed that concentrations were significantly greater for lakes in logged watersheds than for lakes in reference or burned watersheds. Mercury concentrations in pike were above the World Health Organization safe consumption limit for all logged lakes (Garcia and Carignan 2000).

Biotic Effects

Timber harvesting can produce significant environmental impacts that may affect all trophic levels of stream or lake ecosystems. Studies on coastal streams have shown that the major impacts of timber harvesting operations result from increased stream discharge, sedimentation, detrital input (including logs) and water temperature. Increased production of fine sediments, in turn, reduces the availability of benthic habitats for attached algae, aquatic insects and fish. However, recent research on Boreal Shield and Boreal Plain lakes indicate that increased nutrient supply (notably phosphorus) can result in food web alterations. For example, total phosphorus and total organic nitrogen concentrations were significantly higher in Boreal Shield lakes in Quebec in the three years following timber harvest as compared with lakes in undisturbed watersheds (Carignan et al. 2000). In the lakes exposed to timber harvest, a significant increase in phytoplankton abundance was observed in the first year following harvest, an increase that likely would have been even greater if not for lower light penetration caused by inputs of dissolved organic carbon that coloured the water (Planas et al. 2000). On the Boreal Plain, only a small timber cut (15% of the watershed) resulted in a doubling in cyanobacteria abundance and a tenfold increase in an associated hepatotoxin, microcystin-LR; abundance of large zooplankton was also depressed (Prepas et al. 2001). An indirect consequence of timber harvest on aquatic biota arises as a result of road construction and improved access to previously remote regions. This improved access can, for example, lead to overexploitation of fish populations in small lakes.

Agricultural Sector

Water Demands

On a national level, agriculture withdraws a relatively small amount of water (9%) compared to thermal power generation (63%) and manufacturing (19%). However, agriculture consumes a large portion of what it uses, returning less than 30% to its source (Kienholz et al. 2000). About 75% of all agricultural withdrawals of water occur in the semi-arid Prairies. The demand for water is growing for all sectors, increasing the potential for competition and conflict among water users. This situation becomes worse during the droughts that periodically occur in parts of Canada. At least 40 severe droughts have affected western Canada in the past 200 years. Droughts also occur in eastern Canada, but they are usually shorter in duration, smaller in area, and less frequent. The moisture deficit caused by drought places farmland soils at risk, poses a threat to both crop and livestock production, and may result in declines in the quantity and quality of surface and ground waters as more water is diverted to farm operations and less water is available for dilution of pollutants.

Erosion

The introduction of soil into aquatic ecosystems can increase turbidity and thereby reduce plant photosynthesis, interfere with animal behaviours dependent upon sight (e.g., foraging, escaping from predators), impede respiration (by gill abrasion) and feeding, degrade spawning habitat and suffocate eggs. Although much of the sediment in rivers is derived from natural sources, agricultural practices such as tillage and allowing livestock access to streams, increase erosion and the movement of soil from farmland to adjacent waters. Between 1981 and 1996, the risk of soil erosion by water decreased in the Prairie provinces, Ontario and New Brunswick; remained the same in British Columbia and Prince Edward Island; and increased in Quebec and Nova Scotia (Shelton et al. 2000). Although these findings imply a decline in the sedimentation of water courses and water bodies by farm soil, sediment contamination continues to be a serious water quality problem at certain times of the year in many regions, for example in the Maritime provinces where wide-row crops are grown on rolling land with soils susceptible to erosion and in the south coastal region of British Columbia where intensive row cropping of vegetables and berries takes place. To reduce erosion, a number of measures have been implemented including winter cover crop and mulching for row crops, no-till crop production, and a reduction in the Prairies in the area under summerfallow.

Nutrient Losses

Nutrient (nitrogen and phosphorus) addition to aquatic ecosystems promotes excessive growth of algae and rooted aquatic plants, a condition known as eutrophication. As well as increased plant growth resulting as a direct consequence of nutrient addition, indirect consequences include changes in the abundance and reduced diversity of higher trophic levels (e.g., benthic invertebrates and fish), increased abundance of toxic algae, and fish kills caused by loss of oxygen from the water. Eutrophication caused by nutrient loading from agricultural sources has been documented in the Lower Fraser Valley, British Columbia; lakes and rivers in the prairie ecozone; rivers and lakes in the mixedwood plains ecozone of southern Ontario and Quebec; agricultural watersheds throughout the Atlantic provinces and the estuaries and coastal waters into which these rivers flow (Chambers et al. 2001). Nitrogen addition can also stimulate the growth of toxic species of algae in both coastal and inland waters, resulting in contaminated marine shellfish or lake waters.

In addition to the enrichment effects caused by nutrient addition, nitrogen in the form of nitrite can be toxic to humans. Ingestion of high quantities of nitrate may result in methaemoglobinaemia ("Blue Baby Syndrome"), a condition resulting from conversion in the gut of ingested nitrate to nitrite which, in turn, causes oxidation of ferrous (Fe^{2+}) to ferric (Fe^{3+}) iron in haemoglobin, the oxygen carrier of mammalian blood. The resulting methaemoglobin has no oxygen-carrying capacity. The most sensitive subpopulation is infants less than three months of age and the usual source of nitrite is nitrate in drinking water use in formula preparation, with the ingested nitrate converted to nitrite by the microflora of the gut. Nitrate is present in nearly all groundwater underlying the main agricultural regions of Canada. In Canada, 26% of the population, approximately 8 million people, rely on groundwater for domestic water supply (Chambers et al. 2001). Risk of nitrate contamination is highest in areas where there is intensive cropping, high fertilizer inputs, intensive livestock operations, sandy soils, areas of high precipitation or irrigation, and where nitrogen in excess of crop requirements is applied.

Certain forms of nitrogen are also toxic to aquatic organisms and may affect aquatic biodiversity. For example, one factor contributing to the decline in population numbers for 17 of Canada's 45 frog, toad and salamander species is nitrate concentrations in agricultural streams and runoff water that exceed thresholds for chronic and acute toxicity of amphibians (Rouse et al. 1999). Ammonia is also acutely toxic to many aquatic organisms. Results from an assessment of ammonia conducted under the auspices of the *Canadian Environmental Protection Act* (CEPA) indicate that the acute critical toxicity value for freshwater organisms is 0.29 mg/L un-ionized ammonia and the chronic toxicity value for freshwater fish is 0.041 mg/L un-ionized ammonia. Ammonia is not routinely found in Canadian surface waters at high enough concentrations to pose a wide-scale toxic threat to invertebrates or fish. However, an examination of fish kills caused by agricultural activity in Ontario documented 53 fish kills between 1988 to 1998. Most mortalities were caused by spray irrigation of liquid manure to land from swine operations, and lethal effects were attributed to high ammonia or BOD concentrations (K. Tuininga, personal communication, DOE/Ontario).

To reduce inputs of nutrients from agricultural sources to surface and ground waters, efforts have been directed at better managing livestock manure. Many provinces have developed guidelines for manure application and advocate the use of nutrient management plans to ensure environmentally safe manure application. Precision farming will also help to improve the efficiency of fertilizer and manure use.

Pesticide Losses

Pesticides (fungicides, herbicides and insecticides) are used to protect crops against pests and diseases. In 1995, herbicides were used on 67% of Canadian farms. Pesticides are often found in trace amounts in both surface and ground waters in Canada's agricultural regions. Depending upon the compound and concentrations involved, pesticides introduced into surface waters can kill fish and other aquatic organisms; cause sub-lethal effects on reproduction, respiration, growth and development; cause cancer, mutations and fetal deformities in aquatic organisms; inhibit photosynthesis of aquatic plants; and bioaccumulate in an organism's tissues and be biomagnified through the food chain. Although generally below the guidelines for Canadian drinking water quality, pesticide concentrations in surface waters sometimes exceed Canadian water quality guidelines for irrigation water or protection of aquatic life (see examples in Chambers et al. 2000). Most pesticides are applied to the soil. They are transported as aerosols, in surface runoff, and as seepage water. The quantity of pesticides lost from farmland and how it is lost is determined by the nature of the pesticide and the quantity used, weather conditions at the time of application, time elapsed between application and precipitation, slope of the field, and crop production practices.

New techniques for pest control are currently being developed. These include highly selective pesticides that are very specific and less persistent; determination of economic thresholds to support a pesticide application decision; improved application techniques that make pesticides more efficient through selective application to limited areas; genetic induction of pest resistance in plants; using a combination of chemical control and biological control (e.g., use of natural predators, use of pheromones or the release of sterile males); and promoting the growth of beneficial or neutral microoganisms that will help control the growth of detrimental microorganisms.

Heavy Metals

Heavy metals in agricultural soils may be derived from natural or anthropogenic sources. Soil amendments are a major anthropogenic source of heavy metals. The heavy metals in soil amendments of most concern are cadmium, cobalt, chromium, copper, nickel, lead and zinc. Most heavy metals are positively charged cations in soils, and are thus strongly adsorbed to clay particles. The solubility of heavy metal cations generally decreases with increasing clay content and pH. Therefore, fine-textured soils with high pH are less susceptible to runoff or leaching. However, soil loss from agricultural fields can be a major pathway for introducing heavy metals into surface water bodies when heavy metals are adsorbed to soil (Webber and Singh 1995). In addition, heavy metals that form chelated complexes with organic compounds are more susceptible to leaching than non-chelated forms. Heavy metals are of most concern for water quality in terms of protection of aquatic life, as many heavy metals are extremely toxic to aquatic life at low concentrations. For example, the recommended guideline for copper in water to protect aquatic life is between 2 to 4 μg/L.

Soluble Salts

Many prairie soils contain high concentrations of water-soluble salts, including the sulfates of calcium, magnesium and sodium. These salts originate from weathering of the soil parent material. In addition, soil amendments such as livestock manure can contain high concentrations of soluble salts, and long-term application of manure to agricultural land can cause an accumulation of soluble salts in the soil profile. The greatest concern about soluble salts is potential leaching into the groundwater. The risk of groundwater contamination by soluble salts will be higher for coarser-textured soils that have greater leaching because of high precipitation or irrigation. The main concern about soluble salts and groundwater quality is the potential harmful effect on crops irrigated with saline water, as well as the potential harmful impact on livestock that consume saline water.

Pathogens

Pathogenic organisms, including bacteria, protozoa, viruses and parasites, occur naturally in water and soil. Although pathogens occur naturally, pathogens from farm livestock can migrate into groundwater or be carried in runoff into surface waters. Pathogen contamination of irrigation waters, drinking waters or shellfish areas can pose risks to human food supplies. In addition, pathogens can also pose a threat to aquatic ecosystems and biodiversity.

Concerns about pathogenic organisms carried by water from farmland have increased as livestock operations have intensified. Regions of the country with high livestock densities are reporting fecal coliform counts that exceed Canadian water quality guidelines for both drinking and irrigation water (Fairchild et al. 2000). Agricultural runoff is also a major source for bacterial contamination of shellfish, particularly on the Atlantic coast, and has been directly implicated in some shellfish closures. In Ontario, the number of wells with *E. coli* counts exceeding the guideline has almost doubled over the past 45 years from 15% (of 484 wells) in 1950 to 1954, to 25% (of 1292 wells) in 1991 to 1992 (Fairchild et al. 2000).

Endocrine Disrupting Substances

Endocrine disrupting substances (EDSs) are natural and synthetic chemicals that can disrupt the endocrine system, the complex mechanism found in invertebrates, fish, birds and mammals that coordinates and regulates such functions as growth, embryonic development and reproduction. The agriculture sector has been identified as a potential source of endocrine disrupting substances to aquatic ecosystems as a result of runoff or leaching of land-applied manure (which contains natural hormones excreted by livestock), land-applied sewage sludge (which contains natural and synthetic EDSs of human origin), and certain pesticides (which are either directly estrogenic or break down to form estrogenic compounds). Concerns over the potential impacts of substances that disrupt endocrine function in biota in the Canadian environment lead to CEPA 1999 making research on "hormone disrupting substances" a Ministerial duty for both Environment Canada and Health Canada.

Effects of EDSs on development and reproduction have been observed in wildlife in Canada, including: deformities and embryo mortality in birds and fish exposed to industrial chemicals or organochlorine insecticides, impaired reproduction and development in fish exposed to pulp and paper mill effluents, abnormal development of molluscs exposed to antifouling substances applied to the hull of ships, depressed thyroid and immune functions in fish-eating birds in the Great Lakes, and feminization of fish exposed to municipal effluents. Comparatively little is known of the potential risk posed by EDSs from the agricultural sector, although there is evidence that surface water can be impacted by estrogens if runoff or tile drainage occurs shortly after liquid manure from dairy cattle or gestating pigs is applied to land.

Pharmaceuticals

Pharmaceuticals are used for disease prevention and management in livestock and to promote growth. A significant amount of the original substance will leave the organism unmetabolized via urine or feces. Application of manure on fields may result in the movement of pharmaceuticals or their residues to surface or ground waters. Although antibiotic residues in the environment are suspected to induce resistances in bacterial strains and thus cause a serious threat to public health, little is known of the potential risk posed by veterinary pharmaceuticals to environmental or human health.

Knowledge and Program Needs

Understanding the Processes

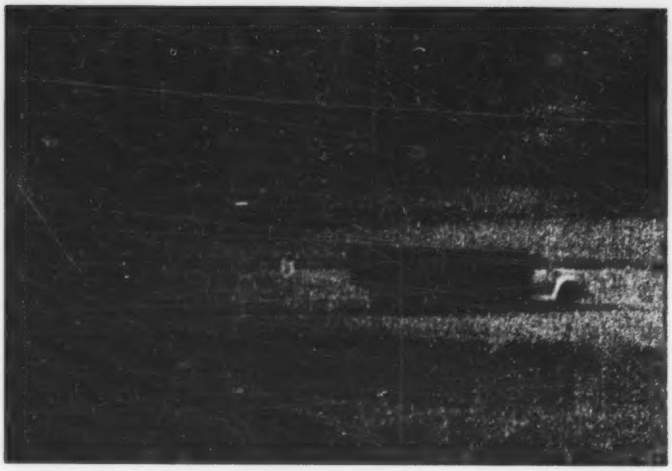
- New or improved mechanistic models are needed that link hydrology and chemical transport from agricultural and forested watersheds to in-stream and in-lake responses such as water yield (streams) or flushing rate (lakes), water chemistry and biotic responses.
- Monitoring networks need to be maintained and accessible to allow assessment of trends over time, evaluate efficacy of new land management practices, and conduct effective watershed management.
- Improved knowledge is required on the regional diversity in processes such as climate, surficial geology and soil characteristics that affect water yield and contaminant movement from agricultural and forest soils.
- Improved understanding is needed of the pathways of chemicals from surface to ground waters and on the discharge/recharge of aquifers most at risk from forestry or agricultural operations (particularly aquifers used as sources of drinking water).
- An improved understanding is required on the fate of pesticides, chemical fertilizer, and nutrients, pathogens, veterinary pharmaceuticals and endocrine disrupting substances in manure and the long-term effects of these substances (individually as well as complex mixtures) on humans, aquatic organisms and their populations and communities.
- A process-level understanding is required of interactions between changing hydrologic regimes and aquatic habitat quality (changing light regimes, thermal regimes, and chemical characteristics).

Risk Analysis and Management

- An improved understanding is needed of methods for assessment and risk analysis of the cumulative effects of agricultural, forestry and other land use activities (e.g., ore, oil and gas exploration) as well as point-source inputs (e.g., municipal and industrial discharges) on surface and ground waters.
- Additional knowledge is needed as to the potential impact on surface and ground waters of agricultural application of biosolids derived from sewage treatment plants.
- Additional knowledge of biogeochemical and hydrological cycles is needed to scale up the effects of perturbations applied over a small area (i.e., disturbances applied to a plot, field or small watershed) to allow prediction of impacts on a broad geographic scale.
- Knowledge is needed as to the impact of land use on nutrient cycling and budgets, and water quality in watersheds. Inputs and outputs of nutrients such as N and P need to be determined so these nutrients can be more effectively managed to prevent surpluses.
- Development of decision support and information systems is required to enable better land use management and protect water sources from the impacts of forestry and agricultural operations.

More intensive use of land already zoned for a particular activity will undoubtedly continue in Canada and will likely increase with population growth and increased demand for forestry and agricultural products. To deal effectively with existing and emerging issues in the management of waters affected by land use change, continued research is required to ensure that new knowledge and technologies are developed for management of lands used for timber harvest, farming or other land-based activities. The following actions are recommended to ensure the protection of water quality from the effects of land use change associated with timber harvest and farming:

- Invest in research on how agricultural and forestry practices affect biogeochemical and hydrological processes; how regional diversity in climate, soil and vegetation modifies the effect of land use practices on these processes; and how land management practices can be altered to minimize impacts.
- Invest in targeted monitoring to determine trends, assess hazards, conduct ecological impact assessments and when warranted, provide for regulatory review, of the effects of timber harvest and agricultural practices on water quality.
- Establish scientifically credible practices, standards, and codes for agriculture and forestry operations, together with appropriate enforcement mechanisms, to ensure protection of ground and surface waters and aquatic biota.
- Incorporate agriculture and forestry practices within integrated watershed management to account for the cumulative effects of numerous environmental stressors.



Timber harvest and agricultural practices affect the quantity and quality of runoff water.

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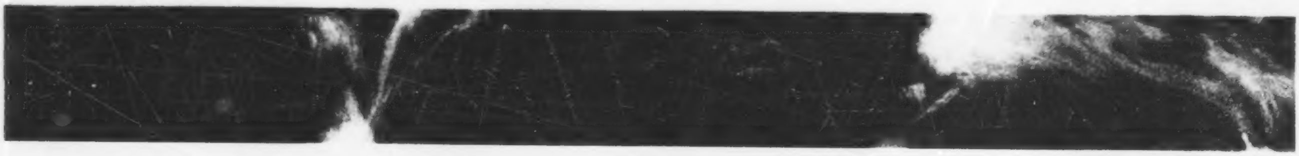

14. NATURAL SOURCES OF TRACE ELEMENT CONTAMINANTS

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Current Status/Trends/Knowledge and Program Needs

Environmental geochemistry is concerned with the abundance, distribution, and mobility of chemical elements in surficial materials at the Earth's surface. Surficial materials are as varied as the scientific disciplines that study them, and include rocks (geology), soils (pedology), sediments (sedimentology, limnology, glaciology), and waters (hydrology). All the materials play critical roles as sources, sinks, and reactive media for trace elements. As a scientific discipline, environmental geochemistry draws on the fields of geology, chemistry, and biology to provide information essential to environmental management, planning, and health protection (Thornton 1995; Knight and Klassen 2001).

Environmental geochemistry is a complex topic. The purpose of this summary is to provide a geological context for geochemical hazards. Emphasis is placed on a small group of naturally occurring elements, chiefly metals and metalloids, derived from geological sources that can represent health risks. The elements include non-metals—fluorine; metalloids—arsenic and selenium; metals—lead, mercury and cadmium; and radioactive elements—uranium, potassium, thorium and radon. The risks they represent are varied, depending on their chemical form and concentration. Although some forms of metals, including chromium, nickel, copper, and zinc can present risk, they can also be bioessential—important for life. Trace element deficiencies are a critical health issue, especially in developing countries where the chemical evolution of surficial materials, hence the chemistry of food and water, can differ profoundly from those of Canada. Worldwide, some 2 billion people are affected by iron, iodine, zinc, selenium and vitamin A deficiencies. Conversely, the arsenic poisoning of thousands of people in Bangladesh and India, that causes skin diseases including cancers, has resulted from the domestic use of naturally contaminated groundwater.

As part of its mandate, Natural Resources Canada provides geoscience expertise and knowledge that is directly related to environmental geochemistry. It has developed geochemical landscape models that portray the origin and composition of surficial materials, and has described the weathering and soil forming processes that affect them. Regional geochemical surveys illustrate the wide range of trace element concentrations that characterize our natural landscape. They clearly identify large areas of potential geochemical hazard where natural concentrations exceed trigger thresholds set by regulatory agencies by one or two orders of magnitude (DiLabio et al. 1999). In central Newfoundland, for example, a 1300-km^2 area is characterized by soil arsenic concentrations of 50 to >1000 ppm; environmental threshold values for contaminated land are typically 20 to 30 ppm (Klassen 1998). In combination, geochemical mapping and research on trace element-mineral associations provides a basis for distinguishing provenance and source identification, i.e., natural versus anthropogenic.

Detailed studies have documented weathering, soil-forming, and hydrogeological processes affecting the movement, concentration, form, and potential bioavailability of trace elements in a wide range of surficial materials, including organic and inorganic soils and sediments, ice, and water (Klassen et al. 2001; Rasmussen 1996). The geological factors that affect geochemistry largely relate to the types of rock-forming minerals that are present and the element form within them. Where either human or natural processes affect the near-surface and soil development, elements associated with weathered and unweathered minerals alike can be released to the air and water, further changing in form, concentration, and potential bioavailability, and becoming more widely distributed in surficial materials. Wind and water for example, can redistribute metal-rich minerals released from roads, agriculture and forestry. Where they are ingested or inhaled, either as particulate or dissolved species, they represent a potential health hazard. Soils, sediments, and rocks in the Eastern Townships of Quebec that are naturally enriched in nickel, magnesium, cobalt, chromium and iron have been implicated in chlorosis, dwarfism, late flush and early senescence of common plants (Bélanger 1988). These metals could be reaching surface and ground water. Crushed pyritic black shale is used locally in the Eastern Townships for road metal, which yields dust, and through weathering, metals which are carried off the roads to waterways by acid rock drainage.

Glacial Transport of Mercury—Central British Columbia

Two of the three mercury mines in Canada were developed along the Pinchi Fault, in British Columbia (Takla Bralorne and Pinchi mines). There, a regional survey (Plouffe 1998) demonstrated high mercury concentrations in till (a sediment type deposited by glaciers) near mines and at other localities along the Pinchi Fault. The mercury is derived from mercury-rich bedrock subjected to glacial erosion during the last glaciation. Through glacial transport, sediments enriched in mercury were transported in a "down-ice direction." Their deposition has resulted in mercury-rich till extending up to twelve kilometres from bedrock sources along the Pinchi Fault. The mercury anomalies (up to 10 ppm) are several orders of magnitude larger than the areas of mercury-rich bedrock, and represent a potential geochemical hazard.

Prairie Soil Geochemistry

In north central Saskatchewan and eastern and central Manitoba, low cadmium and arsenic concentrations in soils reflect the southward glacial transport of cadmium-poor debris derived from the Canadian Shield to the north. In contrast, high cadmium and arsenic concentrations in southwestern Manitoba soils reflect glacial incorporation of trace-element-rich shale bedrock forming the Manitoba Escarpment (Garrett and Thorleifson 1999). In both areas, the geochemical expression of the source is really more extensive in soil than in bedrock as the result of glacial transport.

Where elements are readily dissolved, there can be close compositional linkages between surficial materials and water. Elevated levels of arsenic in groundwater near Cold Lake, Alberta, in some southern Saskatchewan rural municipalities, and at Waverley, Nova Scotia, have all been related to natural sources of arsenic in bedrock and in surficial sediments, and secondary redistribution in both ground and surface waters.

Radioelements

Radioactivity maps have proven highly useful for environmental studies, geological mapping, and mineral exploration, often indicating features not seen by other techniques. Radiation, specifically gamma rays, is emitted through spontaneous decay of radioactive elements. The most common radioactive elements are potassium, uranium and thorium. Potassium, for example, occurs mainly in feldspars, micas and clays, which are abundant and widespread in the Earth's crust. Uranium and thorium are generally present in low concentrations (measured in parts per million) in rocks. Where uranium occurs at high concentrations, it represents a target of economic interest to mining companies. From airborne surveys, using the distinctive gamma ray spectra, the concentrations of potassium, uranium and thorium have been mapped over about 40% of Canada.

Natural radiation exposure: health risks can be associated with long-term exposure to high levels of "natural background" radiation. Airborne gamma-ray surveys provide a measure of natural background radiation coming from the Earth's surface. Radiation exposure levels are expressed in units of microroentgens per hour (μR/h). The Roentgen, which has a precise definition in terms of ionization potential, was originally defined as the amount of radiation required to kill a mouse. It is a useful unit because it can be directly related to physical damage in living cells.

Airborne surveys (Grasty et al. 1984) indicate that there is an average radiation exposure level of 4.4 μR/h for the Canadian land surface (including bedrock outcrops and surficial deposits). United Nations reviews indicate that the average world level is about 5.2 μR/h. Areas of natural radioactivity three times greater than the world average are considered "natural background areas," while areas with levels ten times greater than the world average are considered "high natural background areas."

The Radioactivity Map of Canada shows large parts of the Northwest Territories have areas of elevated radioactivity, in contrast to much of southern Canada, which is characterized by relatively low levels. One area of elevated radioactivity near Fort Smith covers several thousand square kilometres, and is associated with Precambrian granitic bedrock. The granite, with an average radiation exposure level greater than 15 μR/h, has radioelement concentrations of 6.5% potassium oxide, 10 ppm uranium, and 80 ppm thorium. Some areas of more than a hundred square kilometres have twice these concentrations of uranium and thorium. According to the above criteria, the natural background radioactivity of the granite near Fort Smith qualifies as "elevated."

Radon (Nova Scotia): radon (Rn-222), a radioactive gas associated with an increased incidence of lung cancer, is formed by the natural radioactive decay of uranium. Geological mapping of rocks and soils with a potential for high uranium content can be used to interpret regional variations in the concentration of radon in homes. Because of its effects on human health, radon is considered a potential "geochemical hazard" where it occurs at high concentrations.

To determine the linkage between geology and radon gas in homes, the province of Nova Scotia surveyed 719 homes in 75 communities, finding average radon concentrations of 2.9 pCi/L (picocuries/litre). The regional background concentrations are derived from airborne radiometric surveys (Jackson 1992). Areas of high uranium concentration are associated with intrusive rock types, principally the South Mountain Batholith in southwestern Nova Scotia. Four pCi/L is the American standard for radon above which remediation may be recommended. The Canadian standard is 20 pCi/L, and 22 homes out of the 719 surveyed exceeded that standard.

Fluorine in Maritime Groundwater

In the Maritimes, the linkages between geology and groundwater chemistry relate directly to health and land use. Fluoride occurs naturally in rock, entering groundwater by minerals' dissolution. Too much or too little fluoride in drinking water can be harmful to human health. Healthy teeth, for example, require fluoride concentrations to be more than 0.8 ppm and less than 1.5 ppm. However, concentrations greater than 8.0 ppm can result in the crippling disease of skeletal fluorosis. More than half a million people in Newfoundland, Prince Edward Island, Nova Scotia, New Brunswick and eastern Quebec (Gaspé), depend on groundwater derived from the Maritime Carboniferous Sedimentary Basin. In response to both environmental disturbance and geology, fluorine levels vary greatly throughout this region, with potential impact on population health (Boyle and Chagnon 1995).

In 3000 wells in the Carboniferous Sedimentary Basin of New Brunswick, Prince Edward Island and Nova Scotia, the water in approximately 5% has fluoride levels above 1.5 ppm, indicating an increased risk of dental and skeletal fluorosis for populations in these areas.

Trace Element Mobility and Acid Rain

Mineral weathering and element mobility—hence bioavailability, are both affected by water acidity (pH). To assess the potential effects of acid rain on soils, the composition and origins of surficial sediments between Georgian Bay and the Ottawa River Valley were determined (Kettles and Shilts 1994). The area is underlain by two distinct bedrock terrains: the Precambrian Shield and Paleozoic sedimentary rock. Carbonate minerals, which can buffer acid loading in water and surficial deposits that result from acidified rain, are associated with Paleozoic sedimentary rock. In contrast, soils derived from Shield bedrock can be metal-rich, including zinc, arsenic, mercury, and cadmium; where weathering is enhanced by acid loading, they can be released to surface and ground water. Together, geological and geochemical maps can be used to estimate potential soil acidification and trace element mobilization by relating areas enriched in trace elements to carbonate mineral concentrations. The greatest risk for trace metal mobilization in surface water and groundwater exists in areas of low carbonate concentration and high trace element concentrations.

National Geochemical Reconnaissance

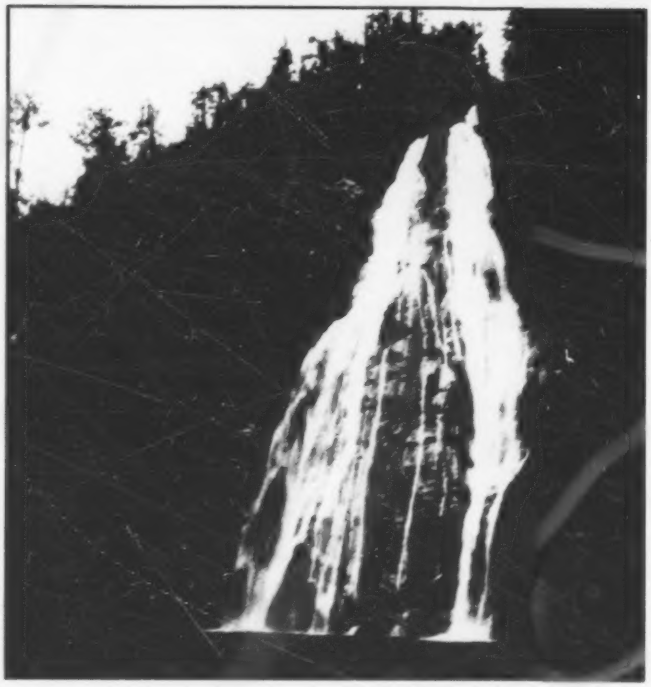
Just as maps are prepared to show the height of the land surface, or percentage of wetlands, maps can be prepared that describe the geochemistry of Canada's surface. Regional geochemical maps may be based on data for different environmental compartments or materials. In Canada, lake and stream sediments have been used to map large areas because they are ubiquitously present in most of the country except the Prairies, Hudson Bay Lowlands and some parts of the High Arctic, and are inferred to represent a >geochemical average=of catchment areas (Friske and Coker 1995).

A mercury map based on 135,000 samples and representing 2.6 million square kilometres shows major variations in the distribution and concentration of mercury across Canada. The most important factors influencing these patterns relate to the geochemistry of bedrock, glacial materials, and soils in the drainage basins (Rasmussen et al. 1997). The vast majority of sample sites are distant from sources of pollution and thus reflect the natural patterns of mercury presence across Canada.

High mercury levels in the Selwyn Basin of southeastern Yukon, the Labrador Trough in western Labrador, and the Rove Basin southwest of Thunder Bay, Ontario, reflect areas where shale occurs. Shale can be formed from organic and sulphur-rich muds that accumulated in an ancient, oxygen-poor environment. Such muds are natural sinks or repositories for mercury and a wide variety of other trace elements. Other areas of higher mercury levels (central B.C. and parts of Vancouver Island) reflect volcanic bedrock. In most of the mercury-rich areas, concentrations are also high in surface waters and soils, and in these areas land disturbance can further release mercury into other environmental compartments.

Bioavailability

A key issue in environmental risk assessment is bioavailability. Unless a trace element is in a form, often referred to as "species" which can cross a biological barrier, it cannot exert a biological effect (Chapman and Wang 2000). Thus, in environmental geochemistry a key focus is on bioavailable element concentrations, which will almost always be less than measured in surficial sediments by methods commonly used by geologists (Garrett 2000). Water—including surface water, groundwater, and pore waters in soils and sediments—is the principal medium for the transfer of dissolved elements between environmental compartments, and a knowledge of the processes involved is critical to environmental geochemistry and hazard assessment. Trace elements having potentially toxic species released from minerals into aqueous solution, including potable water, eventually enter the food chain. Thus, research focus needs to be on water quality and chemistry, and the nature of water-mineral-organic interactions. Processes occurring at water-mineral-organic interfaces are critical to the determination of bioavailability.



Water is the principal vehicle for transfer of dissolved trace element contaminants.

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15. IMPACTS OF DAMS/DIVERSIONS AND CLIMATE CHANGE

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Current Status

This report summarizes the major interactions between water quantity and quality as related to two major issues that have, or will cause, major changes to the hydrologic cycle, i.e., dams/diversions and climate change. Much of our knowledge about such interactions originates from research on the effects of dams/diversions and small-scale process studies that provide a foundation for predicting future impacts from climate change. There are also however, some historical analogues (paleo and recent interdecadal) that can be used to better understand future changes. Other water quantity/quality stressors, such as land use can produce parallel effects but these are not considered explicitly here.

Most of our current knowledge of the impacts of water quantity changes on water quality is based on studies of the effects of Canada's more than 600 dams and 60 large interbasin diversions, which makes the nation the world leader in water diversion (Day and Quinn 1992). Most Canadian dams store water during peak flow periods and release flow to generate power during winter, low-flow periods.

Such changes to water quantity also modify various water quality parameters within the reservoir and downstream, the effects decreasing with distance from the impoundment. Major examples include: thermal stratification within the reservoir and modification of downstream water temperatures; eutrophication; promotion of anoxic conditions in hypolimnetic water and related changes in metal concentrations in outflow; increased methylation of mercury; sediment retention; associated changes in TDS, turbidity and nutrients in the reservoir and discharged water; increased erosion/deposition of downstream sediments and associated contaminants. For impoundments used for drinking water, intra-storage processes also have serious implications for the quality of drinking water.

Flow diversions can also produce major changes in water quality. The most dramatic shifts result from mixing of waters from disparate hydro-ecological systems (e.g., across major hydrologic divides or from freshwater to estuarine environments), resulting in changes in chemistry, temperature and sediment. In addition, the transfer of fish, parasites, and pathogens can accompany such mixing (Day and Quinn 1992).

Variations in climate are also capable of producing major changes in water quantity and thus water quality (Schindler 1997, 2001). Unfortunately long-term data sets of such are rare, the best available trend examples are discussed in the next section followed by predictions of those likely to accrue from climate change.

Trends

Most changes to water quality induced by climate change are driven by alterations to basic precipitation and temperature patterns. Resultant hydrologic extremes such as droughts and floods are especially important. In North America, climate records show there has been a 0.7°C warming of the mean annual air temperature and an increase in precipitation by approximately 70 mm over the last century. These trends have been heterogeneous, with the largest warming occurring in western and northern Canada, and decreasing precipitation in the mid-continent (IPCC 2001). Although comparable long-term water quality records are unavailable, indirect proxy methods (i.e., paleolimnology) can be used. For instance, paleolimnological data on Ellesmere Island ponds indicate after several thousand years of relative stability striking and unprecedented changes occurring over about the last century most likely related to warming and decreased ice cover duration (Douglas et al. 1994). Proxy data from historical sources also show earlier ice breakup and later freezing dates on lakes and rivers around the Northern Hemisphere have occurred over the past century and a half, indicative of changes in the seasonal heat budget of freshwater systems (Magnuson et ai. 2000). Paleo data (e.g., diatoms) from semi-arid regions have recorded striking changes in lake levels and water salinity in response to past droughts.

Dissolved organic carbon (DOC) plays an important role in numerous biogeochemical processes controlling water quality (e.g., metal binding, speciation, bioavailability and transport; nutrient cycling; buffering of acidity), as well as the penetration of UV-damaging radiation. Primarily entering lakes and rivers via runoff, inputs are highly sensitive to precipitation/evaporation ratios. For example, multi-decade data from a boreal catchment affected by drought conditions (decreased precipitation and increased evapotranspiration) showed that exports of DOC decreased by about 50% (Schindler 1997, 2001), although other climatic factors (e.g., radiation, precipitation) are also suspected to be important. In the same regions, concentrated runoff (e.g., increased sulfate, calcium and nutrient concentrations) was observed. The possibility of similar trends in Eastern Canada may be masked by concurrent changes in acid deposition rates.

The most dramatic future changes in water quantity will result from climate change (IPCC 2001). The IPCC concludes that the Canadian climate will be increasingly warmer and wetter, with the North American average mean temperature increasing from 1 to 3°C over the next century for a low emissions case but up to 3.5 to 7.5°C under a higher emission case. Even more rapid warming is expected for the Arctic landmass where winter temperatures are forecast to increase by as much as 2.5 to 14.0°C by 2080. Such changes are also to be accompanied by enhanced evapotranspiration and more frequent extreme events (e.g., floods, droughts). Mid-winter thaw events will also diminish the intensity and magnitude of the spring freshet. Although these changes can be generalized to all regions, there are many unique water quantity/quality impacts that are characteristic of specific regions.

In particular, the sub-Arctic and Arctic are considered to be a bellwether of climate change. This region will experience, for example, the largest rise in mean annual temperatures, significant snowfall increase, earlier snowmelt and ice breakup, melting of permafrost and increased geomorphological disruption most notably in ice-rich permafrost areas, catastrophic lake drainage, and drying of riparian zones and wetlands. Implications for water quality include elevated suspended sediments and increased solute and nutrient concentrations.

For the Great Lakes, decreased precipitation-minus-evaporation and increased frequency of extreme events will result in a general drying and associated reduction in annual streamflow and lake levels, but an increased frequency of flood events. This will produce higher leaching and sediment erosion, increased transport of landscape pollutants, oxidation of terrestrial nitrogen pools, and elevated nitrate transfer to ground and surface water bodies. Reduced DOC exports to lakes and the resulting changes in thermocline depths will affect biogeochemical processes and cold-water biota.

The west coast will experience more extreme spring and summer runoff events resulting in elevated levels of erosion. Further east in the Rocky Mountains, predictions are for an increase in snowfall, but with warmer temperatures the snowline will rise and there will be more winter melts and more frequent rain on snow events. This will lead to changes in the seasonality of streamflow feeding the Prairies with earlier runoff events, and a possible reduction in summer flow. In both western alpine regions, a predicted reduction in snowcover will result in a greater dependence on glacial melt for summer baseflow and hence concentration of major cations and anions.

The Prairies will experience the most pronounced drying of any region in Canada primarily due to greatly increased evapotranspiration. This will reduce streamflow and possibly eliminate prairie sloughs and wetlands. The predicted reductions in water levels will also lead to significant salinization and concentration of other chemical constituents.

In eastern Canada, climate change will lead to the contamination of coastal groundwater resources by saline intrusion as sea level rises, and produce localized drinking water concerns. Furthermore, expected significant decreases in snowcover are predicted to lead to a tripling of solute concentrations in surface water (Moore et al. 1997). In addition, increasing aridity will lead to the elimination of bogs.

Climate change is also predicted to directly and indirectly affect drinking water quality. For example, severe runoff events are expected to increase surface to groundwater contamination. More indirectly, higher summer water temperatures and longer periods of stable stratification are likely to promote the dominance (blooms) of various cyanobacteria and chrysophytes that can affect taste and odour and the production of toxins that have serious human health implications. Such algal blooms can also impact the ecological integrity of aquatic ecosystems through indiscriminant kills of fish and invertebrates due to oxygen depletion and damage or clogging of their gills (Hallegraeff 1993).

Emerging Issues

A number of key emerging issues can be identified dealing with the linkages between climate change/water diversions and water quality impacts.

Water Balance and Water Quality

Projected changes in the precipitation/evaporation ratio will affect the water levels of ponds, lakes and wetlands. For example, in the case of prairie ponds/dugouts employed for drinking water, declines in water levels will lead to altered water chemistry, particularly including increased salinization. This will lead to a major reduction of the availability of rural drinking water, especially within semi-arid regions. Furthermore, these water-quality changes will produce significant indirect effects on drinking water status such as increased toxins and taste and odour problems related to algal blooms. Another critical concern related to changing water levels is the retention capacity of existing tailings ponds designed under current climate conditions. If future precipitation exceeds evaporation, these systems will become prone to overtopping and spillage into the local flow network. Moreover, retention of toxic compounds in northern systems may be further threatened by the forecasted reduction in permafrost that is currently relied on as an aquitard that prevents leakage to groundwater.

Extreme Events and Water Contamination

The forecasted increase in the frequency and magnitude of extreme events (precipitation, runoff and snowmelt events) will compromise contaminant storage, processing and transport. The design of most current sewage treatment facilities are unlikely to accommodate the increased volume of stormwater and sewage runoff. This will lead to decreased processing efficiency and the bypassing of municipal and industrial wastes to the receiving environment. Similarly, extreme events will enhance the transport of urban landscape contaminants (e.g., pesticides, salts, coliform bacteria) directly into lakes and rivers, thereby reducing their water quality and use. In addition, extreme precipitation and associated runoff will enhance exports of nitrates and wastes from agricultural fields and increase overland transport of chemical and bacteriological contaminants to surface and ground water. The erosive capacity of extreme runoff events could reduce the stability of earthen-based retention structures located adjacent to rivers and lead to catastrophic input of stored contaminants to, e.g., tar sands ponds.

Hydrologic Cycle and Toxins

Interactions between changes in hydrologic regimes and toxins will be complex and wide ranging but vary by geographic region. For instance, in areas that will have decreased water inputs (either through runoff or precipitation), the delivery of pesticides from polluted lands to water is expected to decrease, while their retention in lakes and ponds will increase due to increased water residency. Projected increases in temperature will enhance decomposition of pesticides, PCBs and other semi-volatile organics and result in revolitization of these compounds and mercury. The result will be a reduction in concentrations in southern aquatic systems and their transport to colder, northern latitudes. Even then, however, warming of cold regions and the associated reduction in freshwater ice cover and enhancement of mixing processes will result in many northern lakes and ponds becoming new contaminant sinks. Increased water temperatures will also increase food chain uptake and transfers of contaminants. This is of particular concern to Aboriginal communities that rely on aquatic systems for traditional lifestyles.

Climate Change and Biogeochemical Cycling

Climate change is expected to have significant effects on biogeochemical processes within ecosystems, some of which are brought about by interactions with acidification, eutrophication and the DOC cycle. In the case of acidification, reduced precipitation and runoff results in lower water tables in catchments and shrinkage of wetlands. This, in turn, results in changes in redox processes that substantially alter stream and lake chemistry. Reduced base-cation supply from surface and ground waters during dry periods may also affect water quality. As a consequence, recovery of lakes following sulphur emission controls should be delayed. Similarly, changes in runoff and water temperature could affect the nutrient status of aquatic ecosystems. Specifically, nutrient loadings and their cycling will be altered, as will physical properties such as thermal stratification that controls respiration and related dissolved oxygen levels. Changes in DOC in turn can profoundly affect the physical and chemical quality of ecosystems, including the penetration of potentially harmful UV. There is recent evidence that DOC decreases in lakes as a result of catchment drying and associated reduced runoff. There is also evidence that DOC levels can be controlled by incident UV radiation. Furthermore, it has been postulated that the acidification of lakes alters the DOC concentrations. Many other synergistic or antagonistic relationships are possible. However, the mechanisms for any of these changes are unclear. Such changes in DOC accompanied by climate-induced alterations in the hydrologic and physical environment will also influence the transport and bioavailability of contaminants such as mercury, lead, copper and other metals.

Climate Change and Habitat Alteration/Loss

Changes in local runoff and water balances will produce major changes to the types and availability of aquatic systems. For example, in semi-arid regions, first-order streams may become ephemeral or absent. Similarly, as occurred under slight warming (<1–2°C) in the Holocene, many ponds and wetlands will completely disappear and lakes will become increasingly disconnected from their drainage systems. Major associated water quality and productivity changes (i.e., altered growth rates, life cycles, generation times of biota) will accompany the drying of these systems, and significantly affect those remaining. Warmer thermal regimes will create conditions more conducive to the invasion of warm-water species and the competitive replacement and extinction of native species. Furthermore, warming will lead to a reduction in the range (both in altitude and latitude) of some cold water, stenothermic species (e.g., increasing temperatures eliminating habitat for brook trout at the southern end of their range) (Lodge 1993; Rahel et al. 1996). Projected increases in water demand and use will also enhance the need for interbasin water transfers or diversions, contributing further to physical habitat alterations of both the donor and recipient basins, corresponding alterations in their water quality, and the potential introduction of foreign biota and disease.

Knowledge and Program Needs

To ensure that we have the required scientific knowledge to address the above noted emerging issues, we require:

- An improvement in climate forecast scenarios, especially for the magnitudes and regional variations in precipitation.
- More knowledge about water balance in altered landscapes (snow and ice resources, permafrost melting, altered storage capacity).
- An improved ability to downscale GCM/RCM data for use in hydrological and ecological models.
- A detailed understanding of the interactions between hydrological processes and biogeochemical responses, particularly with respect to interactions with acid deposition and redox processes, DOC cycling, UV penetration, contaminant (e.g., mercury) transport, speciation, and bioaccumulation, and nutrient cycling.
- Knowledge of the effects of changes in water quantity/quality on ecosystem structure and function (e.g., predicting conditions conducive to algal bloom outbreaks).
- A process-level understanding of interactions between changing hydrologic regimes and aquatic habitat quality (changing light regimes, thermal regimes, and chemical characteristics [e.g., oxygen levels]).
- A predictive understanding of how changes in the climate system affect the hydrologic cycle (e.g., timing, duration, and magnitude of extreme events) and thereby pose a threat to the treatment, transport and storage of poor quality water. The duration over which time this will occur is unknown, nor have many of the mechanisms and consequences been studied adequately.

- Development of integrated process-based studies and models for assessing and predicting climate change-induced changes to hydrologic and biogeochemical processes as they relate to critical water quality issues (e.g., acidification, eutrophication, and the transport and bioavailability of contaminants).
- Establishment or enhancement of instrumented basins in representative hydroclimatic regions, especially where water quality is predicted to be most significantly modified by climate change (e.g., semi-arid region, arctic bellwether, Great Lakes/St. Lawrence basins, deltaic estuarine systems).
- Establishment of a Canadian Hydro-Ecology Research Network (CHERN) to coordinate and facilitate multidisciplinary research assessing the effects of climate change on water quality as they relate to drinking water, ecosystem integrity and integrated basin management of water resources.
- Establishment of an international comparative circumpolar research network (CP-HERN) to act as an international bellwether of climate impacts on water resources (linkages to International Arctic Science Committee [IASC], UNESCO-MAB Northern Science Network and UNESCO-IHP-VI).
- Conduct an assessment of present water treatment and storage facilities regarding their capacity to deal with future hydrologic changes, particularly the increased frequency and magnitude of extreme events.

Ice breakup on the Mackenzie and Liard rivers: historical sources show earlier ice breakup and later freezing dates on lakes and rivers in recent years.

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